2nd Virtual Geoscience Conference

Proceedings Volume

22 - 23 September 2016

21 September (Short Courses)

Grand Terminus Hotel
Bergen, Norway

Uni Research AS
http://virtualoutcrop.com/vgc2016

Where Geomatics Meets Geoscience

Uni Research CIPR 2016
Editors: Simon J. Buckley, Nicole Naumann, Tobias H. Kurz, Christian H. Eide
ISBN: 978-82-8361-004-8 (printed)
ISBN: 978-82-8361-005-5 (pdf)

How to Cite

Proceedings volume:

BUCKLEY, S.J., NAUMANN, N., KURZ, T.H. &EIDE C.H. (Eds.), 2016. *2nd Virtual Geoscience Conference, Proceedings Volume*, Uni Research CIPR, Bergen, Norway: 212 pages.

Individual contribution:

DEWEZ, T.J.B., PLAT, E., DEGAS, M., RICHARD, T., PANNET, P., THUON, Y., MEIRE, B., WATELET, J.-M., CAUVIN, L., LUCAS, J. & DIAN, G., 2016. Handheld mobile laser scanners Zeb-1 and Zeb-Revo to map an underground quarry and its above-ground surroundings. *Proceedings of the 2nd Virtual Geoscience Conference*, Bergen, Norway, 21-23 September 2016: 5-6.


WHERE GEOMATICS MEETS GEOSCIENCE
2nd Virtual Geoscience Conference 2016
VGC 2016
21 - 23 September 2016
Grand Terminus Hotel
Bergen, Norway
VOG
uni Research

Sponsors

All sponsors of VGC 2016 are sincerely thanked for their generous financial support, without which it would not have been possible to arrange the conference.

Partners

The organisers thank all partner organisations for their support in promoting VGC 2016, financial assistance (where relevant), and general encouragement to make the conference an attractive international event.

VGC Media Partners

Table of Contents

Where Geomatics Meets Geoscience

An international conference organised by the Virtual Outcrop Geology (VOG) Group, Bergen

Scope

The VGC series focuses on novel developments and applications of close range remote sensing methods within the broad field of geoscience research. As the current state-of-the-art of spatial mapping in geoscience is trending towards convergence between many fields (e.g. geomatics, computer vision, graphics, visualization, geostatistics and numerical modelling, as well as the sub-disciplines of earth science), acquiring and working with 3D and 2D image data has never been so accessible. This has resulted in a dazzling array of new applications in many areas and at many scales, and across the academic, public and private sectors. The result is an exciting new realm of scientific research, and the purpose of the VGC series is to offer a meeting place for researchers who are actively working with techniques such as lidar or photogrammetry, develop analysis methods based on these input data, or are considering starting to work in this field.

Background

The 1st VGC took place at the University of Lausanne, Switzerland, organised by the Risk Analysis Group in February 2014. At this time, the conference was called "Vertical Geology", to designate the focus of interest to be mostly connected to near-vertical geological exposures and associated surface processes, as opposed to traditional remote sensing applications based on aerial and satellite (nadir) field of views, where coverage of steep topography was poor. To encompass the broader range of applications in geoscience, the series was renamed to Virtual Geoscience, with the aim of attracting a wider range of geomatics researchers and geoscientists, and riding on a wave of new developments associated with relevant innovations in computer science, such as virtual and augmented reality, which is sure to be a stronger feature of future events. Finally, the series should foster cross-disciplinary discussion and interaction, allowing growth and collaboration, rather than restricting dialogue to the respective sub-disciplines.

Response

Following on from the successful VGC 2014 meeting, the response to the 2016 event was characterised by breadth and growth. Nearly 110 abstracts were submitted, based on a call in spring 2016, with representation by internationally-leading groups in geomatics and geoscience research. In addition, public sector bodies (e.g. geological surveys) were strong contributors, showing the way geomatics methods are moving from the research domain to general utilisation. Norway, with its special situation in terms of topography and climate, is a leader in the field. Two short courses were run on Virtual Geoscience and CloudCompare, and the conference co-hosted the 3rd IQmulus project workshop. All technical contributions were reviewed by the scientific committee, contributing to intense competition for oral presentations, which were limited by number of days available. The final programme, comprising 2 keynote speeches, 41 orals and over 55 posters, truly gives a flavour of the current state-of-the-art of virtual geoscience.

Presentation formats

In addition to conventional oral and poster presentations, five contributions were selected for **Interactive** presentation at the conference. As the conference theme is highly visual, and based on high technology and novel software, traditional 2D slides and posters do not always do the content justice. Interactive presentations were therefore introduced to allow authors with specific hardware, software developments or particularly impressive datasets to showcase their methods and results. Because Interactive contributions were offered to two of the oral presenters, to supplement their presentations, relevant abstracts appear in both the oral and poster sessions, rather than having a dedicated section. The Technical Programme identifies the specific abstracts selected for Interactive presentation.

Acknowledgements

The organising committee acknowledges the important contribution of the scientific committee to the development of the final programme, mainly characterised by the need to perform a high number of reviews to ensure at least two referees were used for each submission. In addition, all partner organisations and sponsors are thanked for aiding the promotion of the conference and giving financial support to ensure a successful international conference could be organised in Norway. Thanks to Daniel Girardeau-Montaut for running the CloudCompare short course. Finally, the local organising team, comprising the administration of the host institute (K. Haug, K. Kristiansen, M. Entner, I.S. Thorsen), A. Graven in Uni Research, and helpers from the University of Bergen (M. Flesland, I. Aarsland, K. Alvestad, M. Kjenes, I. Blækken, S.S. Ågotnes, J. Magnus, M.T. Horne), provided essential assistance in administrative and logistical support.

A note on terminology

Where possible, terminology (spelling, abbreviations, formatting) has been edited to follow listings according to GRANSHAW (2016). This serves to add uniformity to what can be disparate use of common terms (lidar, LiDAR, LIDAR, LADAR, laserscanning, laser scanning, TLS, T-LiDAR etc. being one common example). The cited reference is adopted by the International Society of Photogrammetry and Remote Sensing (ISPRS).

GRANSHAW, S.I., 2016. Photogrammetric Terminology: Third Edition. *Photogrammetric Record*, 31(154): 210-251.

Simon J. Buckley

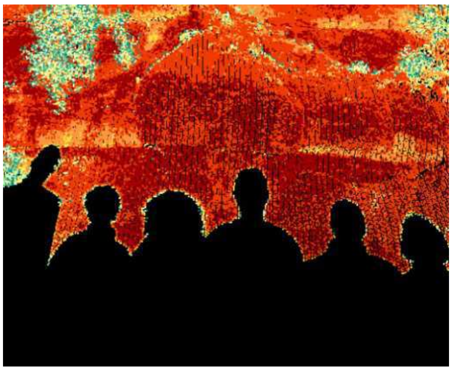
Nicole Naumann

Tobias H. Kurz

Christian H. Eide

September 2016

Committees



Conference Chair

Dr Simon J Buckley

Local Organising Committee

Dr Simon J Buckley *VOG, Uni Research, Norway*

Dr Nicole Naumann *VOG, Uni Research, Norway*

Dr Tobias Kurz *VOG, Uni Research, Norway*

Dr Christian Haug Eide *Department of Earth Science, University of Bergen, Norway*

Scientific Committee

Prof Andrea Bistacchi *(University of Milano Bicocca, Italy)*

Prof Jim Chandler *(University of Loughborough, UK)*

Dr Brian Collins *(USGS, USA)*

Dr Marc-Henri Derron *(University of Lausanne, Switzerland)*

Dr Thomas Dewez *(BRGM, France)*

Dr Bernhard Höfle *(Heidelberg University, Germany)*

Prof John Howell *(University of Aberdeen, UK)*

Prof Michel Jaboyedoff (University of Lausanne, Switzerland)

Dr Michael James *(Lancaster University, UK)*

Prof Andreas Kääb *(University of Oslo, Norway)*

Dr Zhizhong Kang *(China University of Geosciences, P.R. China)*

Dr Matt Lato *(BGC Engineering, Canada)*

Dr Ping Lu *(Tongji University, P.R. China)*

Dr Richard Murphy *(University of Sydney, Australia)*

Dr Thierry Oppikofer *(Norwegian Geological Survey, Norway)*

Prof Marco Scaioni *(Politecnico di Milano, Italy)*

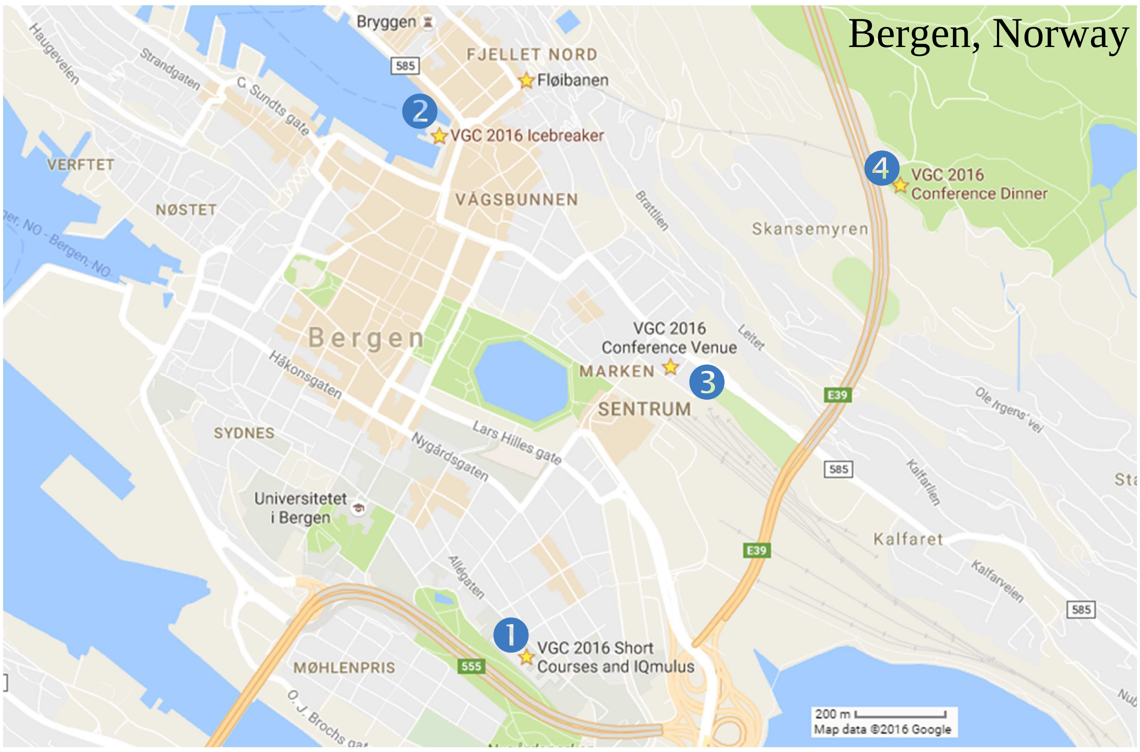
Dr John Thurmond *(Statoil, USA)*

Dr Sophie Viseur *(Aix-Marseilles University, France)*

Practical Information

Locations and contacts

21/9	Short Courses and 3rd IQmulus Workshop Venue • Virtual Geoscience • CloudCompare • 3rd IQmulus Workshop	Realfagbygget (Natural Science Building), Allégaten 41, University of Bergen • Rooms 3G10e (3rd floor) and Fjellhallen (2nd floor) • Room CIPR 4060 (4th floor) • Room 4A10b (4th floor)	❶
	Icebreaker	Zachariasbryggen, Torget 2, Bergen	❷
22/9	Conference Venue *Oral & poster presentations*	Grand Terminus Hotel, Zander Kaaes gate 6, Bergen *Terminus Hall & Terminus Forum*	❸
	Conference Dinner	Fløien Folkerestaurant, Fløyfjellet 2, Bergen	❹
23/9	Conference Venue *Orals & panel discussion*	Grand Terminus Hotel, Zander Kaaes gate 6, Bergen *Terminus Hall & Terminus Forum*	❸



Keynotes

The importance of geomatics in mapping and monitoring geohazards in Norway

Lars Harald Blikra, Norwegian Water Resources and Energy Directorate

Norway's topography provides some unique challenges in terms of safety and infrastructure, which must be managed to protect human life and ensure a modern communication and transport network. Different types of landslides occur regularly, especially in western Norway, typified by deep valleys and fjords stretching for many kilometres inland. Falling rock masses entering the fjord system can cause tsunamis and flooding, giving failures potentially catastrophic consequences for local populations. This gives a societal obligation to manage risk and provide early warning – exemplified by a major programme for rockslide management and monitoring in Norway. Here, geomatics methods are playing their part in identification, site characterisation and monitoring, providing a showcase application for the theme of VGC 2016. In his keynote speech, Prof Blikra will give an overview of this important geohazard affecting Norwegian society, and how geomatics is integrated into an array of mapping and monitoring techniques that are used for managing risk and uncertainty.

Lars Harald Blikra is Head of Section for Rockslide Management at the Norwegian Water Resources and Energy Directorate (NVE), as well as an Adjunct Professor at the University of Tromsø. He has a background in geology and is internationally-recognised for his work on landslide characterisation.

The potential of visualization and visual data analysis in geoscience

Helwig Hauser, Visualization Group, University of Bergen

Geoscientists acquire an increasing amount of rich spatial data in order to support their research. With increased data volumes as well as with increased heterogeneity of the acquired data, the utilization of modern analysis and visualization technology becomes important. The field of visualization offers high-performance techniques for visualization, for example, exploiting graphics hardware, as well as advanced methods for the interactive visual analysis of rich geoscientific data. In this talk, we review the potential of modern visualization technology in the field of geoscience. In particular, we sketch an answer to the question of how advanced visualization is more than just rendering 2D pictures from 3D scenes.

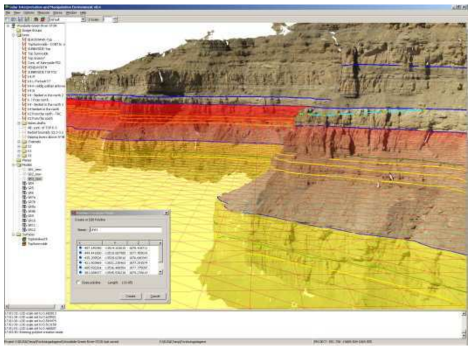
Since 2007, Helwig Hauser has been professor of visualization at the University of Bergen, Norway, where he leads a research group in the field of visualization at the Department of Informatics. He has around 20 years of experience in visualization research with a major focus on application-oriented basic research. The topic of visualization for the geosciences is one of the central research topics in the Visualization research group in Bergen.

Short Courses

1. Virtual Geoscience

A short course covering 3D measurement techniques, hyperspectral imaging and interpretation for geoscience applications will be aimed at PhD students, early career researchers (ERCs) and anybody with an interest in learning how methods such as lidar, photogrammetry and spectral imaging can be employed in their own work.

Terrestrial laser scanning (lidar) and photogrammetry are being widely adopted in geoscience research for obtaining topographic datasets. In addition, complementary hyperspectral imagers measure reflected light with high spectral resolution, allowing material properties to be analysed remotely. Close range hyperspectral imaging is currently seeing increased interest, especially through integration with lidar geometric data.



Controlling a terrestrial laser scanner using the on-board wifi interface, not just a bunch of people playing on their smartphones ;-). Right; interpretation using LIME.

In the course we will cover aspects of data collection and processing and then focus on practical exercises allowing participants to learn more about interpretation, analysis and visualisation of 3D models, using the LIME software.

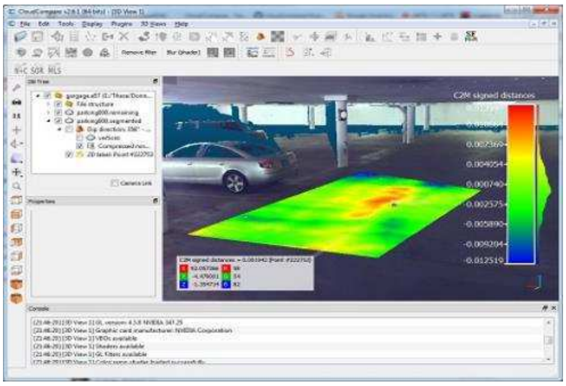
Practical information:

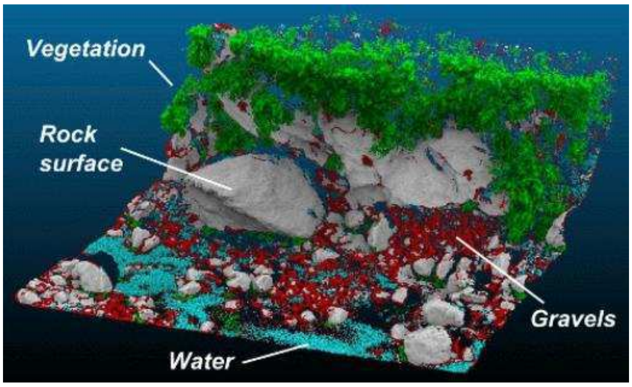
Computer exercises will take place in the university's computing facilities: computers, software and datasets provided.

Course holders:	Dr Simon Buckley & Dr Tobias Kurz (Uni Research CIPR)
Time:	09:00-17:00
Location:	Room 3G10e (3rd floor), Realfagbygget (Natural Science Building), Allégaten 41, University of Bergen

*2. **CloudCompare** with Daniel Girardeau-Montaut*

CloudCompare is open source software designed for high performance point cloud processing. Initially developed for comparing 3D point clouds (change/difference detection) it has, over time, become a general and well-respected point cloud processing utility, with many users around the world. The software includes advanced algorithms such as registration, resampling, handling of colour, normal and scalar fields, computation of statistics, segmentation and display enhancement. In addition, plugins are available implementing state-of-the-art algorithms reported in the scientific literature.





In this short course, CloudCompare's creator and lead developer, Daniel Girardeau-Montaut, will give an overview of the software, including elements such as registration, cloud to cloud comparison and plugins. The course is aimed at all participants with an interest in learning more about practical point cloud processing.

Practical information:

Participants should bring their own laptop computers if possible (or be prepared to work together on practical components).

Course holder:	Dr Daniel Girardeau-Montaut
Time:	09:00-17:00
Location:	Room: CIPR 4060 (4th floor), Realfagbygget (Natural Science Building), Allégaten 41, University of Bergen

IQmulus Workshop

VGC 2016 will play host to the third (and final) IQmulus Workshop on 21st September. IQmulus is an ongoing Integrating Project (IP), partially funded by the European Commission (2012-2016), and comprising 12 partners from 7 countries in Europe. IQmulus focuses on developing a point cloud handling platform that provides the needed functionalities to integrate latest research results in data processing and visualization to tackle important real-life challenges in geospatial applications. The workshop will allow participants to present their latest findings. The agenda is published on the project's website.

Workshop organiser:	Tor Dokken, (SINTEF)
Location:	Room 4A10b (4th floor), Realfagbygget (Natural Science Building), Allégaten 41, University of Bergen/Uni Research
Time:	11:30-18:00

More information about the IQmulus project is available at: http://iqmulus.eu/

A High-volume Fusion and Analysis Platform for Geospatial Point Clouds, Coverages and Volumetric Data Sets

Technical Programme

Wednesday, 21 September 2016

<table>
<tr><td>08:30 – 09:00</td><td colspan="3">Registration and Morning Coffee(UiB RFB*, 4th floor)</td></tr>
<tr><td rowspan="2">09:00 – 10:30</td><td>Short Course:
Virtual Geoscience</td><td>Short Course:
CloudCompare</td><td>IQmulus Workshop</td></tr>
<tr><td>Session 1
Room: 3G10e
UiB RFB*, 3rd floor</td><td>Session 1
Room: CIPR 4060
UiB RFB*, 4th floor</td><td rowspan="8">Room: 4A10b
UiB RFB*, 4th floor</td></tr>
<tr><td>10:30 – 11:00</td><td colspan="2">Coffee Break</td></tr>
<tr><td>11:00 – 12:30</td><td>Session 2
Room: 3G10e
UiB RFB, 3rd floor</td><td>Session 2
Room: CIPR 4060
UiB RFB, 4th floor</td></tr>
<tr><td>12:30 – 13:30</td><td colspan="2">Lunch</td></tr>
<tr><td>13:30 – 15:00</td><td>Session 3
Room: Fjellhallen
UiB RFB, 2nd floor</td><td>Session 3
Room: CIPR 4060
UiB RFB, 4th floor</td></tr>
<tr><td>15:00 – 15:30</td><td colspan="2">Coffee Break</td></tr>
<tr><td>15:30 – 17:00</td><td>Session 4
Room: Fjellhallen
UiB RFB, 2nd floor</td><td>Session 4
Room: CIPR 4060
UiB RFB, 4th floor</td></tr>
<tr><td>19:00 – 22:00</td><td colspan="3">Conference Icebreaker: Mikrobryggeriet, Zachariasbryggen</td></tr>
</table>

** UiB RFB: Realfagbygget (Natural Science Building), Allégaten 41, University of Bergen.*

Thursday 22nd September, A.M.

<table>
<tr><td>08:00 – 08:30</td><td colspan="2">Registration and Morning Coffee</td></tr>
<tr><td rowspan="2">08:30 – 10:30</td><td colspan="2">Terminus Hall</td></tr>
<tr><td colspan="2">Welcome and Conference Opening
Keynote: The importance of geomatics in mapping and monitoring geohazards in Norway
<u>Lars Harald Blikra</u>, Norwegian Water Resources and Energy Directorate, Norway

Chair: Michel Jaboyedoff, University of Lausanne
Handheld mobile laser scanners Zeb-1 and Zeb-Revo to map an underground quarry and its above-ground surroundings
<u>Thomas Dewez</u>, BRGM - French Geological Survey, France

Increasing safety along rock fall exposed highway sections by using ground-based radar and RPAS captured photography
<u>Regula Frauenfelder</u>, Norwegian Geotechnical Institute (NGI), Norway

Optimising UAV topographic surveys processed with structure from motion: Ground control and bundle adjustment
<u>Mike R. James</u>, Lancaster University, UK</td></tr>
<tr><td>10:30 – 11:00</td><td colspan="2">Coffee Break</td></tr>
<tr><td rowspan="2">11:00 – 12:20</td><td>Terminus Hall</td><td>Terminus Forum</td></tr>
<tr><td>Chair: Marc-Henri Derron, University of Lausanne
Insights from constant near-realtime laser scanning of actively failing rockslopes
<u>Nick Rosser</u>, Durham University, UK

Fast surveying of a sea cliff and a landslide based on structure from motion photogrammetry
<u>Giordano Teza</u>, University of Padua, Italy

GB-InSAR and lidar for mapping and predicting slide events in steep terrain
<u>Lene Kristensen</u>, Norwegian Water Resources and Energy Directorate, Norway

3D change detection analysis of a coastal landslide performed by multi-temporal point cloud comparison
<u>Giuseppe Esposito</u>, University of Siena, Italy</td><td>Chair: Roderik Lindenbergh, TU Delft
The potential of non-semantic features for UAV remote sensing data fusion
<u>Eduard Angelats</u>, CTTC, Geomatics Division, Spain

An approach for considering beam divergence in voxel space transformation of full-waveform airborne laser scanning data
<u>Nadine Stelling</u>, TU Dresden, Germany

Using high-resolution digital surface models for wetland water level assessment
<u>Marko Kohv</u>, University of Tartu, Estonia

Technical aspects related to monitoring riverbank erosion in mountain catchments using point clouds
<u>Marco Scaioni</u>, Politecnico di Milano, Italy</td></tr>
<tr><td>12:20 – 13:30</td><td colspan="2">Lunch</td></tr>
</table>

Thursday 22nd September, P.M.

<table>
<tr><td rowspan="2">13:30 – 14:30</td><td>Terminus Hall</td><td>Terminus Forum</td></tr>
<tr><td>Chair: Luc Girod, University of Oslo

Detailed glacier crevasse morphology mapped by helicopter
Christopher Nuth, University of Oslo, Norway

Multi-temporal UAV-survey of a calving glacier in Northwest Greenland
Yvo Weidmann, ETH Zürich VAW, Switzerland

Is it worth going up there?
Fanny Brun, Université Grenobles Alpes, France</td><td>Chair: Mike James, Lancaster University

Photogrammetric analysis of lava dome growth using digital photography and thermal imaging: Volcán de Colima 2013-2015
Sam Thiele, Monash University, Australia

Laboratory geodesy: Application of open-source photogrammetric software MicMac to monitor surface deformation in laboratory models
Olivier Galland, University of Oslo, Norway

Mapping lava flow morphology and structure with unmanned aerial vehicles
Einat Lev, Columbia University, USA</td></tr>
<tr><td>14:30 – 15:00</td><td colspan="2">Coffee Break</td></tr>
<tr><td rowspan="2">15:00 – 16:00</td><td colspan="2">Terminus Hall</td></tr>
<tr><td colspan="2">Chair: Jim Chandler, Loughborough University

UAV studies of terrestrial analogs for Martian geology
Jeffrey E. Moersch, University of Tennessee, USA

PRo3D®: A tool for geological analysis of Martian rover-derived digital outcrop models†
Robert Barnes, Imperial College London, UK

Listening to 3D topography data with interactive sonification†
Karen Mair, University of Oslo, Norway

Announcement: Introduction to Poster Session</td></tr>
<tr><td>16:00 – 18:15</td><td colspan="2">Chair: Tobias Kurz, Uni Research
Poster and Interactive Session‡, Aperitif</td></tr>
<tr><td>19:15 – 22:30</td><td colspan="2">Conference Dinner, Fløien Folkerestaurant</td></tr>
</table>

† Denotes supplementary presentation during Interactive Session.

‡ Poster and Interactive presentations are detailed below.

Friday 23rd September, A.M.

<table>
<tr><td>08:00 – 08:30</td><td colspan="2">Registration and Morning Coffee</td></tr>
<tr><td rowspan="2">08:30 – 10:15</td><td colspan="2">Terminus Hall</td></tr>
<tr><td colspan="2">Keynote: The potential of visualisation and visual data analysis in geoscience
<u>Helwig Hauser</u>, University of Bergen, Norway

Chair: Thomas Dewez, BRGM – French Geological Survey

Exfoliation sheets detection with terrestrial laser scanning and thermal imaging (Yosemite Valley, California, USA)
<u>Antoine Guerin</u>, University of Lausanne, Switzerland

Simulated full-waveform laser scanning of outcrops for development of point cloud analysis algorithms and survey planning: An application of the HELIOS lidar simulation framework
<u>Sebastian Bechtold</u>, Heidelberg University, Germany

Geological Registration and Interpretation Toolbox (GRIT): A visual and interactive approach for geological interpretation in the field
<u>Christian Kehl</u>, Uni Research AS, Norway</td></tr>
<tr><td>10:15 – 10:40</td><td colspan="2">Coffee Break</td></tr>
<tr><td rowspan="2">10:40 – 12:00</td><td>Terminus Hall</td><td>Terminus Forum</td></tr>
<tr><td>Chair: John Howell, University of Aberdeen

Fracture network characterisation using multi-scale UAV imagery, line extraction and stochastic simulation tools
<u>Roderik Lindenbergh</u>, TU Delft, The Netherlands

3D modelling of fractures from DOM and field data: Characterization of spatial distribution patterns in fracture corridors
<u>Sophie Viseur</u>, Aix-Marseille Université, France

Advances in the automated geometric extraction and analysis of geological bodies from virtual outcrops
<u>Björn Nyberg</u>, University of Bergen, Norway

Fault extraction using multi-remote sensing images
<u>Li Wei</u>, Northwest University, China</td><td>Chair: Daniel Wujanz, TU Berlin

Surface roughness analysis of fossil oyster shells using 3D laser scanning data
<u>Ana Djuricic</u>, Vienna University of Technology, Austria

Determination of roughness parameters based on dense image matching and structured light scanning
<u>Kristofer Marsch</u>, Technische Universität Berlin, Germany

Characterization of geological structures with technical improvements in acquisition and processing
<u>David García-Sellés</u>, University of Barcelona, Spain

Distinguishing facade material change using close-range hyperspectral imaging
<u>Zohreh Zahiri</u>, University College Dublin, Ireland</td></tr>
<tr><td>12:00 – 13:00</td><td colspan="2">Lunch</td></tr>
</table>

Friday 23rd September, P.M.

	Terminus Hall	Terminus Forum
13:00 – 14:20	**Chair: Sophie Viseur, Aix-Marseilles Université**	**Chair: Nick Rosser, Durham University**
	Geostatistics and modelling algorithms for characterisation of sandstone intrusions *David Hodgetts, University of Manchester, UK*	HPC implementation of image correlation techniques for monitoring slow-moving landslides with Sentinel-2 time series *Jean-Philippe Malet, University of Strasbourg, France*
	Virtual outcrop mapping for CO_2 reservoir analogue modelling *Davide Pistellato, University of Queensland, Australia*	Object-based change analysis of terrestrial laser scanning point clouds for shallow landslide monitoring *Andreas Mayr, University of Innsbruck, Austria*
	Utilisation of three-dimensional models in Exploration *Jens Grimsgaard, Statoil Research & Technology, Norway*	Quantification of intact rock bridges and rock mass fragmentation after failure by means of remote sensing techniques *Margherita Cecilia Spreafico, University of Bologna, Italy*
	Lidar, photogrammetry & field measurements from Stackpole Quay: Contrasting methods and implications for structural model building and predictions *Adam Cawood, University of Aberdeen, UK*	Development of a TLS real-time monitoring system for landslides *Ryan Kromer, Queen's University, Canada/ University of Lausanne, Switzerland*
14:20 – 14:50	Coffee Break	
14:50 – 15:30	**Terminus Hall**	
	Chair: Nicole Naumann, Uni Research	
	Surface kinematics of periglacial sorted circles over 8 years using SfM close range photogrammetry *Andreas Kääb, University of Oslo, Norway*	
	The application of UAV acquired photogrammetric models in natural disaster mitigation: Volcanic monitoring and crowd-sourced flood modelling *John Howell, University of Aberdeen, UK*	
15:30 – 16:40	**Panel Discussion: Issues, trends and the future of Virtual Geoscience** Moderator: Simon Buckley **Closing Remarks**	

Poster and Interactive Presentations, 22nd September

Interactive Presentations

PRo3D®: A tool for geological analysis of Martian rover-derived digital outcrop models
Robert Barnes, Imperial College London, UK

Collaborative and immersive analytics to support stratigraphic survey
Marcelo Kehl de Souza, Vale do Rio dos Sinos University, Brazil

Listening to 3D topography data with interactive sonification
Karen Mair & Natasha Barrett, University of Oslo, Norway

From photorealistic outcrop models to synthetic seismic images
Kari Ringdal, Uni Research, Norway

Mapping Paleoproterozoic meta-volcanic rocks using photogrammetry
Erik Vest Sørensen, Geological Survey of Denmark and Greenland (GEUS), Denmark

Poster Presentations

An evaluation of low cost consumer-grade UAS systems for 3D reality capture
Dietmar Backes, University College London, UK

Investigating snow cover volumes and icings dynamics in the moraine of an Arctic catchment using UAV/ photogrammetry and lidar
Eric Bernard, University of Franche Comté, France

GB-InSAR and terrestrial laser point clouds for characterising the transient deformation pattern of a large gravitational instability during rainfall events
Pierrick Bornemann, University of Strasbourg, France

Point cloud time series for monitoring landslide processes: displacement field analysis using image correlation and optical flow algorithms
Pierrick Bornemann, University of Strasbourg, France

Information system for subsurface geological data: Find the best solution for the State of Geneva
Maud Brentini & Stéphanie Favre, University of Geneva, Switzerland

Extended temporal scale of Transantarctic outlet glacier hypsometry using stereographic techniques with historic aerial photographs
Sarah F. Child, University of Kansas, USA

Evaluating roughness scaling properties of natural active fault surfaces by means of photogrammetry
Amerigo Corradetti, University of Naples Federico II, Italy

Reservoir-scale fracture characterization from an inaccessible carbonate analogue: a UAV photogrammetry application to geology

Amerigo Corradetti, University of Naples Federico II, Italy

Distributed processing of Dutch AHN laser altimetry changes

Máté Cserép, Eötvös Loránd University, Hungary

Seismic imaging of deeply emplaced mafic sill complexes

Christian H. Eide, University of Bergen, Norway

Clay mineral mapping in underground potash mines using corrected intensity lidar data at 905 nm

Angus F.C. Errington, University of Saskatchewan, Canada

User-guided structural interpretation toolbox for digital outcrop models

Marie Etchebes, Schlumberger Stavanger Research Center, Norway

Rockfall source area detection and characterisation from terrestrial laser scanner (TLS) data

David García-Sellés, University of Barcelona, Spain

Opportunistic survey of glaciers using low-cost equipment

Luc Girod, University of Oslo, Norway

Generation of 3D models using panoramic camera for indoor and outdoor scenarios: system calibration, test and first results

Nives Grasso, Politecnico di Torino, Italy

Multi-temporal DEM extraction using archival aerial photos: Case study of the Czarny Dunajec River, Polish Carpathians

Maciej Hajdukiewicz, Kielce University of Technology, Poland

3D displacement retrieval on a scaled model of mountain slope by virtual multi-view photogrammetry

Haixing He, University of Savoie, France

High-resolution model of the Bilila-Mtakataka Fault, Malawi using Pleiades stereo-imagery and UAV-based structure from motion

Michael Hodge, Cardiff University, UK

Object-based time series analysis for landslide change detection using optical remote sensing imagery: Examples from Austria and Norway

Daniel Hölbling, University of Salzburg, Austria

Detection of surface water changes using TerraSAR-X data for flood hazard monitoring

Katherine Irwin, Queen's University, Canada

Time-lapse cameras and structure from motion algorithms: Continuous three-dimensional monitoring in geosciences

Andreas Kaiser, Technical University Bergakademie Freiberg, Germany

Digital taphonomic model as a tool to improve viewing of a bivalve mollusc-dominated fossil biofabric

<u>Marcelo Kehl de Souza</u>, Vale do Rio dos Sinos University, Brazil

Low-cost 3D scanning technique for digital outcrop modelling based on multiple view images

<u>Marcelo Kehl de Souza</u>, Vale do Rio dos Sinos University, Brazil

Multispectral spectroscopy as a tool for detection of surfaces and stacking patterns in a carbonate-siliciclastic basin to support sequence stratigraphy

<u>Marcelo Kehl de Souza</u>, Vale do Rio dos Sinos University, Brazil

Reflectance spectroscopy applied to the lithological characterization of Permo-Carboniferous siltstones and organic shales found in the Paraná Basin, Brazil

<u>Marcelo Kehl de Souza</u>, Vale do Rio dos Sinos University, Brazil

Unravelling the structure of the ocean-continent transition from high resolution, photo-based 3D reconstructions of onshore dyke complexes

<u>Moritz Kirsch</u>, Helmholtz-Institut Freiberg für Ressourcentechnologie, Germany

Application of photogrammetry for mapping of natural solution collapse breccia pipes in the Grand Canyon, USA

<u>Matthias Klawitter</u>, University of Queensland, Australia

The 3D visualization and analysis of fracturing by using laser scanning data, geological maps and geophysical data - study sites from Southern Finland

<u>Eevaliisa Laine</u>, Geological Survey of Finland, Finland

Rockfall monitoring of a poorly consolidated marly sandstone cliff by TLS and IR thermography

<u>Caroline Lefeuvre</u>, University of Lausanne, Switzerland

Natural neighbour kriging and its potential for quality mapping

<u>Roderick Lindenbergh</u>, TU Delft, The Netherlands

Virtual analogues of Ypresian carbonated fractured reservoir at Ousselat Cliff (Central Tunisia) using terrestrial laser scanning and GigaPan techniques

<u>Raja Mastouri</u>, University of Lausanne, Switzerland

Interpretation of compound dune dynamics using imagery and internal structure analysis

<u>Alexandre Medeiros de Carvalho</u>, Universidade Federal do Ceará-UFC, Brazil

Use of GIS, regional thematic data and site-specific procedures to assess/rank environmental risks at large scale: The Campania region case study

<u>Giulia Minolfi</u>, University of Naples Federico II, Italy

From virtual outcrop models to multiple point statistics training images for improved reservoir modelling

<u>James Mullins</u>, University of Aberdeen, UK

Automated mapping of discontinuities within Cretaceous dolerite sills, Central Spitsbergen, Arctic Norway

Mark J. Mulrooney, University Centre in Svalbard (UNIS), Norway

Quantitative mapping of absorption by water, phyllosilicates and sulphate on a geological outcrop

Richard J. Murphy, University of Sydney, Australia

Insight on the contribution of photogrammetry and UAVs to the mapping and monitoring of unstable rock slopes

Pierrick Nicolet, Geological Survey of Norway (NGU), Norway

Photogrammetric study of fracture surface roughness in shale rocks

Marcin Olkowicz, Polish Geological Institute – National Research Institute, Poland

Understanding heterogeneity in aeolian reservoir analogues using virtual outcrop models

Colm Pierce, University of Aberdeen, UK

Observing ground deformation phenomena: High resolution topography data from remote to proximal sensing

Luca Pizzimenti, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy

Repeated boat-borne lidar survey to quantify coastal erosion in Carry-le-Rouet (southern France)

Mélody Prémaillon, Université de Toulouse, France

High resolution glacier monitoring over Nigardsbreen, Norway, using a GoPro camera and an acrobatic plane

Benjamin Aubrey Robson, University of Bergen, Norway

Photogrammetry with DJI Phantom 2 drone: 3D model of an area deformed by neotectonics in the Venezuelan Andes

Riccardo Rocca, unaffiliated, Spain

Integrating geophysical equipment and UAV technology: Considerations and limitations

Maxime Salman, University of Waterloo, Canada

State of the art 3D visualization of geotopes: A case study of the Cornberg Sandstone

Thomas Schmitz, Technische Universität Darmstadt, Germany

Making the Arctic accessible: The use of digital outcrops in research and education at 78°N

Kim Senger, University Centre in Svalbard (UNIS), Norway

Change detection using baselines extracted from single scans demonstrated on a masonry wall subject to seismic testing

Yueqian Shen, TU Delft, The Netherlands

Detailed structural mapping of syn-rift deposits by incorporating lidar data in reservoir modelling software

Espen Sigmundstad, University of Stavanger, Norway

Three-dimensional model of facies distribution within a Triassic half-graben, SW Edgeøya, Svalbard
Aleksandra Smyrak-Sikora, University Centre in Svalbard (UNIS), Norway

Regional geological 3D-mapping in Alpine terrain: An example of a large oblique image-block from West Greenland
Erik Vest Sørensen, Geological Survey of Denmark and Greenland (GEUS), Denmark

Mapping mountain-scale thrust zones using photogrammetry: Examples from the French Alps
Yukitsugu Totake, University of Aberdeen, UK

Across spatial scales: Snow depth from combined satellite and airborne lidar
Désirée Treichler, University of Oslo, Norway

Mapping geological structure on mountain-scale photogrammetric models generated from national survey vertical aerial photos (Kamnik Alps, Slovenia)
Marko Vrabec, University of Ljubljana, Slovenia

Suitability of terrestrial lidar and digital photogrammetry for surveying and analysis of fold structures
Bianca Wagner, University of Göttingen, Germany

Use of terrestrial laser scanning data in monitoring anthropogenic objects and landscape elements
Janina Zaczek-Peplinska, Warsaw University of Technology, Poland

Integrating UAV-based photogrammetry to improve digital outcrop model quality
Ruisong Zhou, University of Illinois at Urbana-Champaign, USA

Conference Contributions

Session 1

Chair: Michel Jaboyedoff
University of Lausanne

Terminus Hall

Thursday 8:30 – 10:30, 22nd September

Handheld mobile laser scanners Zeb-1 and Zeb-Revo to map an underground quarry and its above-ground surroundings

Thomas J.B. Dewez[1*], Emmanuelle Plat[1], Marie Degas[2], Thomas Richard[2], Pierre Pannet[1], Ysoline Thuon[1], Baptiste Meire[1], Jean-Marc Watelet[2], Laurent Cauvin[2], Joël Lucas[3] & Graham Dian[3]

[1]*BRGM French Geological Survey,45060 Orléans la Source, France, t.dewez@brgm.fr*
[2] *INERIS, French Industrial Environment and Risks Institute, 60550 Verneuil-en-Halatte, France*
[3]*Geoperspectives Géomètres experts, 75014 Paris, France*

Key words: *lidar, handheld mobile scanner, Zebedee, underground mapping, 3D point cloud.*

Underground quarries are typically difficult environments for 3D mapping. They are dark, wet, dusty, have limited lines of sight and are full of hidden corners behind pillars. These properties call for a dense succession of active measurement (using some kind of light) stations with hardened materials. Once mapped, the next obvious question creeps up, how does this cavity relate to the above-ground world? The Zebedee range of handheld mobile laser scanner was designed by CSIRO to address just this question. We have tested a Zebedee-1 (Zeb-1) and a Zebedee-Revo (Zeb-Revo) in an abandoned underground quarry. The initial purpose of the work was to assess the equipment in mapping a sector of a quarry and its above-ground surroundings. In a second phase, we examined how the full 3D dataset was to be processed to retrieve pertinent metrics for geotechnical purposes.

The investigated site is located in the abandoned limestone quarry at Saint-Maximin (Oise, Northern France), where INERIS, within the framework of the R&D part of the "Plan National Cavités", a French programme dedicated to cavity risk assessment, managed by the French Ministry in charge of Environment, created an underground experiment and demonstration unit. This laboratory site is dedicated to investigate underground cavity risks and operated in collaboration with Saint-Maximin town council, owners, and the "Maison de la Pierre", manager of the site.

The Zebedee range of handheld mobile laser scanners exists as Zeb-1 and the recent Zeb-Revo. Both are time-of-flight line scanning lidar coupled with an inertial mapping unit so as to locate the moving lidar head in space and time. The scanning plane freely oscillates on a spring (Zeb-1) or rotates around a horizontal axis in order to scan a sphere portion surrounding the holder. A 90° blind zone enables the holder to hide behind the scanning head and avoid being scanned inside the scene. The lidar distance meter has a nominal precision of 5 mm + 1 mm/m with a maximum range of 30 m. Scanning density is 40 lines per second for Zeb-1 and 100 lines per second for Zeb-Revo. Both line scanners cover three quarters of a circle line made of 42,000 shots. A 3-axes accelerometer measures the attitude of the scanning head. Black-box simultaneous location and mapping algorithm (SLAM) build 3D cloud from these measurements assuming that the surfaces where points rebound off are rigid and non-deformable. Near-neighbour point redundancy is used to make points converge towards a unique surface. Processed outputs include 3D points in LAZ format, various decimated cloud versions and 3D Zeb head trajectory.

Surveys are established as 15 to 20 minutes hikes walking nearly at normal pace (~ 2-3 km/h) looping back to the original starting point. Here, we walked four loops of 1000 m to 1500 m to survey 0.8 ha of underground galleries and 1.8 ha of above-ground streets. Sufficient overlap between loops should be achieved to register loops together. One of the loops had too little overlap with the others, hence a loss of 0.45 ha of underground area impossible to tie to the rest of the survey.

Zebedee systems produce 3D point clouds with only 4 degrees of freedom (scale and horizontal are established – XYZ coordinates relative to a local origin and initial bearing to north are unknown), compared to the 6-degrees-of-freedoms of terrestrial laser scanners (TLS, where scale is known) or 7-degrees-of-freedom Structure from Motion surveys (no rotation, translation or scale known).

Were Zeb surveys any good? Point precision was assessed using two perfectly planar surfaces ca. 30 m² each. These reference planes were advertisement posters fixed on the Maison de la Pierre façade and made of tarpaulin held in tension on metal frames. Precision estimates correspond to point-to-plane deviation and come to ± 25.5 mm and 32.2 mm respectively (Q66% of residuals) for a Zeb-Revo trajectory comprised between 0.5 m and 10 m away from the planes (Tab. 1).

Table 1: Zeb-REVO point precision assessment on two planar surfaces. Point precision is the deviation with respect to the best-fitting plane. (S=Surface)

	Nb pts [-]	Length [m]	Width [m]	Surface [m²]	Point density [pts/m²] Q2.5%	Q50%	Q97.5%	Point spacing [mm/pts] Q2.5%	Q50%	Q97.5%	Point precision 1-σ [mm]	Q17-Q83 [mm]
S1	113 512	8.34	3.46	28.85	3 300	13 350	19 271	17.4	8.7	7.2	28.6	25.5
S2	57 259	9.12	3.22	29.37	1 953	5 501	11 165	22.6	13.5	9.5	35.5	32.2

Above ground, median point spacing was respectively 8.7 mm and 13.5 mm on the modelled reference planes. Underground, point density in 3-m-high galleries reached median point spacing of 1 point every 15 mm. (Tab. 1). This degree of surface description is amazingly dense and fast compared to current compass/rangefinder cavity surveys.

As is standard with TLS, post-processing of raw 3D clouds involves registering individual loops together into a complete survey, and cleaning up stray points. Loop registration is today rather difficult because the scanner's own relative coordinate origin and initial azimuth are unknown. Given these two unknowns, visual recognition of common gallery sections are far more challenging than matching sequential TLS "bubble" clouds where the same problem also exists. Once coarsely matched, however, cloud to cloud fine alignment can be performed just as well.

Raw Zeb clouds do contain parasite points, often because the operator's body was scanned when it happened to come out of the lidar's blind corner. These points float in midair. Cleaning them can rely on distance between the point cloud and the Zeb head's 3D trajectory and on local point density estimates.

Once together, new information can be teased out of the 3D cloud. Most geotechnically relevant information however require the point cloud to bear some semantics: floor, walls and ceilings, underground and above ground points, pillars versus surrounding chamber walls. Segmentation can be performed with tools such as CloudCompare combined with its plugin FACETS (DEWEZ *et al.*, 2016). Floor and ceilings can be segmented as being above or below the Zeb trajectory, while walls and floor/ceiling can be isolated using their normal with the interactive stereogram tool of the plugin FACETS.

At St Maximin, galleries are generally sound. In one specific location however, a gallery roof is known to collapse occasionally. At present, the roof is at 10.05 m at the highest above gallery floor, while there is only 9.35 m of over-lying terrain.

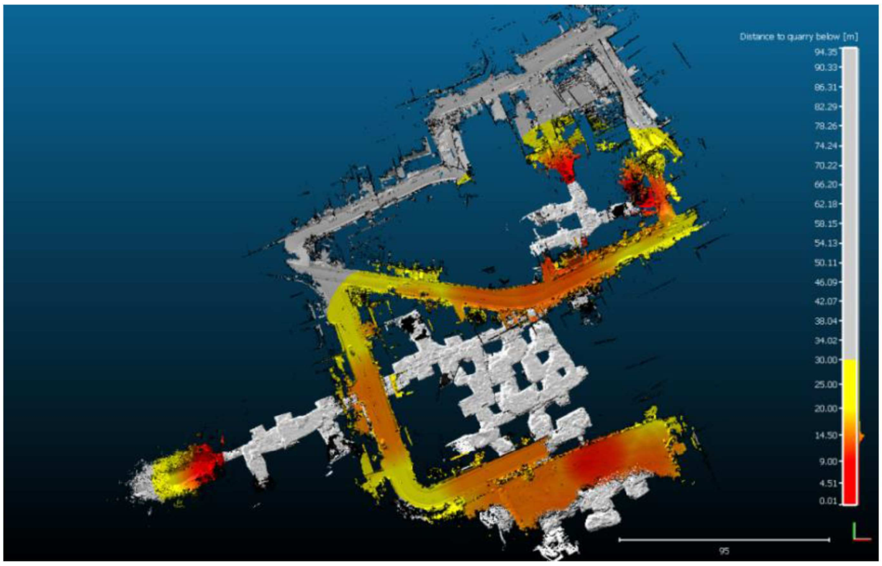


Figure 1: Map view of 1.8 ha of above ground streets (in warm tones) and 0.8 ha of underground galleries (light gray) of the St Maximin building stone quarry (Oise, Northern France) mapped with a Zebedee Revo in March 2016. Colours depict the distance to the nearest gallery points.

Reference

DEWEZ, T.J.B., GIRARDEAU-MONTAUT, D., ALLANIC, C., ROHMER, J., 2016. FACETS: a CloudCompare plugin to extract geological planes from unstructured 3D point clouds. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B5, 799-804.

Increasing safety along rock fall exposed highway sections by using ground-based radar and RPAS captured photography

Kristine Ekseth[1], Malte Vöge[1], Helge Smebye[1], Regula Frauenfelder[1*], Asgeir Kydland Lysdahl[1] & Andreas A. Pfaffhuber[1]

[1] *Norwegian Geotechnical Institute NGI, P.O. Box 3930, N-0806 Oslo, Norway;*
[*]regula.frauenfelder@ngi.no

Key words: *ground-based interferometry, photogrammetry, RPAS, PlaneDetect.*

Up to 900 meters high mountain slopes with frequent rock fall makes the E16 between Bergen and Gudvangen an exposed stretch of road.

The Norwegian Geotechnical Institute monitors parts of E16 in Hordaland and Sogn og Fjordane on behalf of the Norwegian Public Roads Administration. The purpose of the monitoring is to warn where rock fall might occur, so that the road authorities can effectuate the necessary mitigation measures. The mountain slopes along the road are so high and complex that it is impossible to secure the rock faces everywhere. Therefore, monitoring was implemented at six sites with notorious rock fall events, especially during periods of heavy rainfall.

We use a Gamma Portable Radar Interferometer (GPRI) to monitor the rock fall sites. Such ground-based radars have a fixed location for all measurements of an object. The method uses the difference in radar signal between data acquisitions in order to detect movements of the measured surface over time. Differences in such radar images over time can reveal movements down to millimetre scale. For optimal visualization, the results of the measurements are draped over 3-dimensional surface models gained through the photogrammetric processing of a multitude of photographs captured from a Remotely Piloted Aircraft System (Fig. 1).

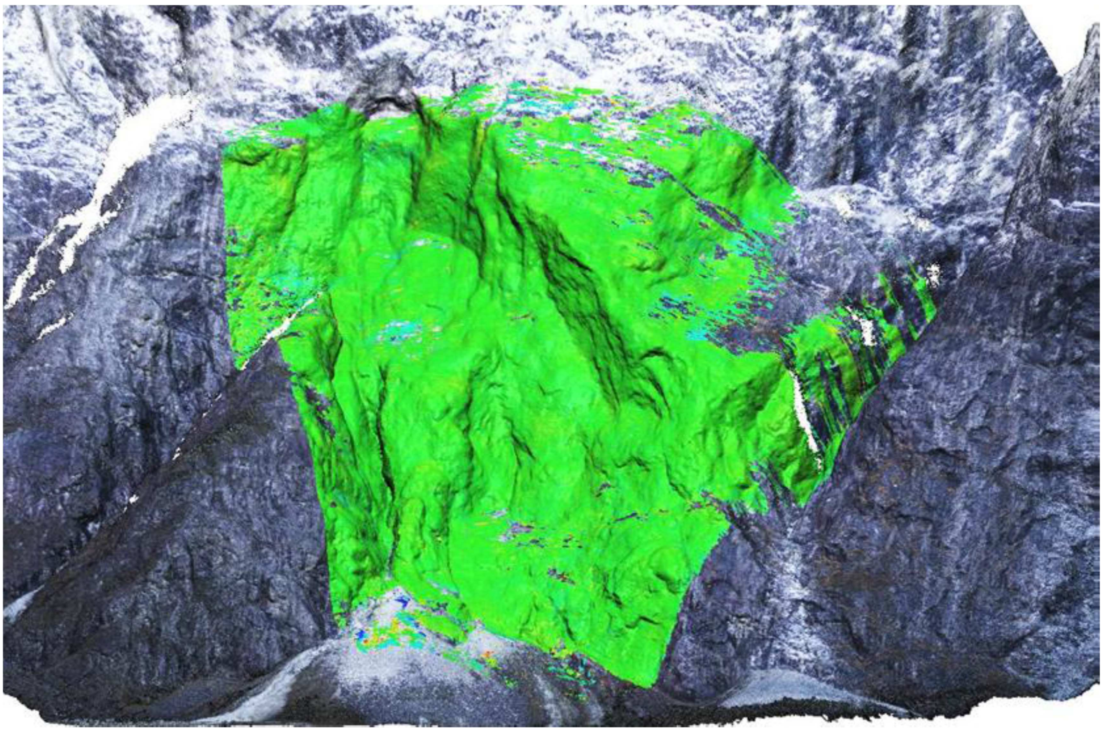


Figure 1: GPRI result (change detection between Nov. 2015 and April 2016) of one of the survey areas draped over a 3-dimensional surface model derived from RPAS captured imagery. Green areas are considered stable. The yellow line outlines areas with block accumulation (blue) and block evacuation (red to yellow) in the talus cone below the rock wall.

The first measurement series was conducted in autumn 2014 which is used as a baseline. By now, we have conducted three additional series of radar measurements. The measurements happen twice a year, in spring and autumn. So far during the project period, no significant movements were observed in the surveyed areas.

Where meaningful, the acquired data is analysed with the software PlaneDetect (cf. VÖGE *et al.*, 2013) which allows for the automated identification and mapping of planar discontinuities within the 3-dimensional surface models. The software outputs a stereonet of discontinuity orientations coloured by joint set family, an image of the 3-dimensional model with each mapped discontinuity coloured by the set family, and a text file of discontinuity orientations (Fig. 2). The time saving realized through using PlaneDetect for mapping discontinuities is approximately ten times compared to the manual mapping approaches and is, in addition, more statistically reliable due to less user bias.

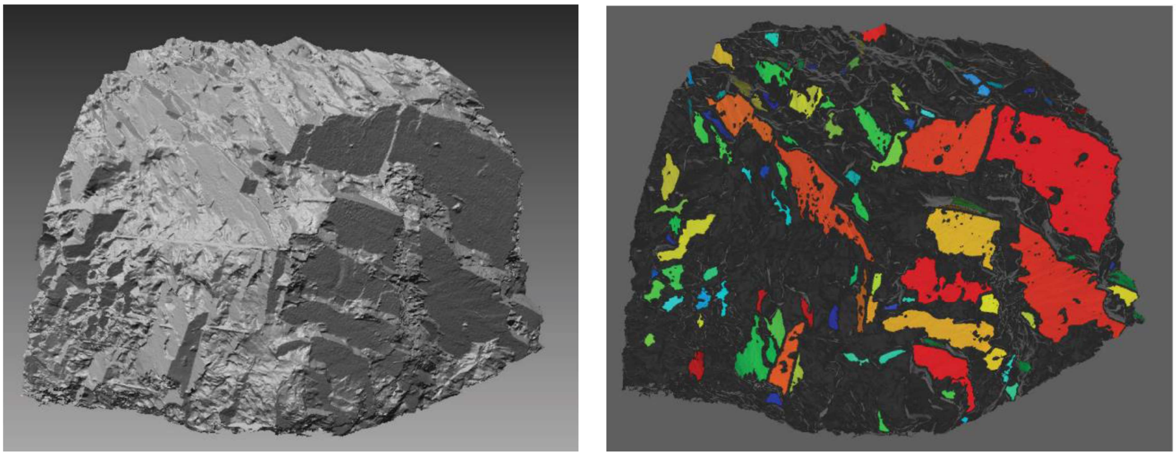


Figure 2: left) 3D model of surveyed rock section; right) the same model as left, now coloured by joint set family after processing in PlaneDetect.

Acknowledgements: We would like to acknowledge our client the Norwegian Public Roads Administration (SVV) for allowing us to share our results with the scientific community and our contact persons at NPRA Mr Harald Hauso and Mr Knut Tøn.

Reference

VÖGE, M., LATO, M.J., DIEDERICHS, M.S, 2013. Automated rockmass discontinuity mapping from 3-dimensional surface data. *Engineering Geology*, 164: 155-162.

Optimising UAV topographic surveys processed with structure from motion: Ground control and bundle adjustment

Mike R. James[1*], Stuart Robson[2] & Sebastian d'Oleire-Oltmanns[3]
& Uwe Niethammer[4]

[1] *Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, U.K.; m.james@lancs.ac.uk*
[2] *Dept. Civil, Environmental and Geomatic Engineering, University College London, Gower Street, London, WC1E 6BT, U.K.*
[3] *Dept. Geoinformatics - Z_GIS, University of Salzburg, Salzburg, A-5020 Salzburg, Austria*
[4] *Universität Stuttgart, Institut für Geophysik, Azenbergstr. 16, 70174 Stuttgart, Germany*

Key words: *UAVs, ground control, structure from motion, bundle adjustment.*

Structure from motion (SfM) algorithms are greatly facilitating the production of detailed topographic models, often using images collected by unmanned aerial vehicles (UAVs). However, SfM-based software does not generally provide the rigorous photogrammetric analysis required to fully understand survey quality. Consequently, error related to problems in processing settings, control point data or the distribution of control can remain undiscovered. Even if these are not large in magnitude, they can be systematic, and thus have strong implications for the use of products such as digital elevation models (DEMs) and orthophotos. Here, we develop a Monte Carlo approach to (1) improve the accuracy of products when SfM-based processing is used and (2) reduce the associated field effort by identifying suitable lower density deployments of ground control points. The method highlights issues such as overparameterisation during camera self-calibration and provides enhanced insight into control point performance when rigorous error metrics are not available.

Processing was implemented using commonly-used SfM-based software (PhotoScan Pro v.1.1.6), which we augment with semi-automated and automated GCPs image measurement. We apply the Monte Carlo method to two contrasting case studies – an erosion gully survey (Taurodont, Marocco) carried out with a fixed-wing UAV, and an active landslide survey (Super-Sauze, France), acquired using a manually controlled quadcopter. The results highlight the differences in the control requirements for the two sites, and we explore the implications for future surveys.

We illustrate DEM sensitivity to software processing settings that are not generally discussed for SfM geoscience surveys but are critical for suitably weighting tie point and control point measurements (Fig. 1). Appropriate settings values can be determined by considering the RMS of image residual magnitudes, and this increases DEM repeatability and reduces the spatial variability of error due to processing artefacts.

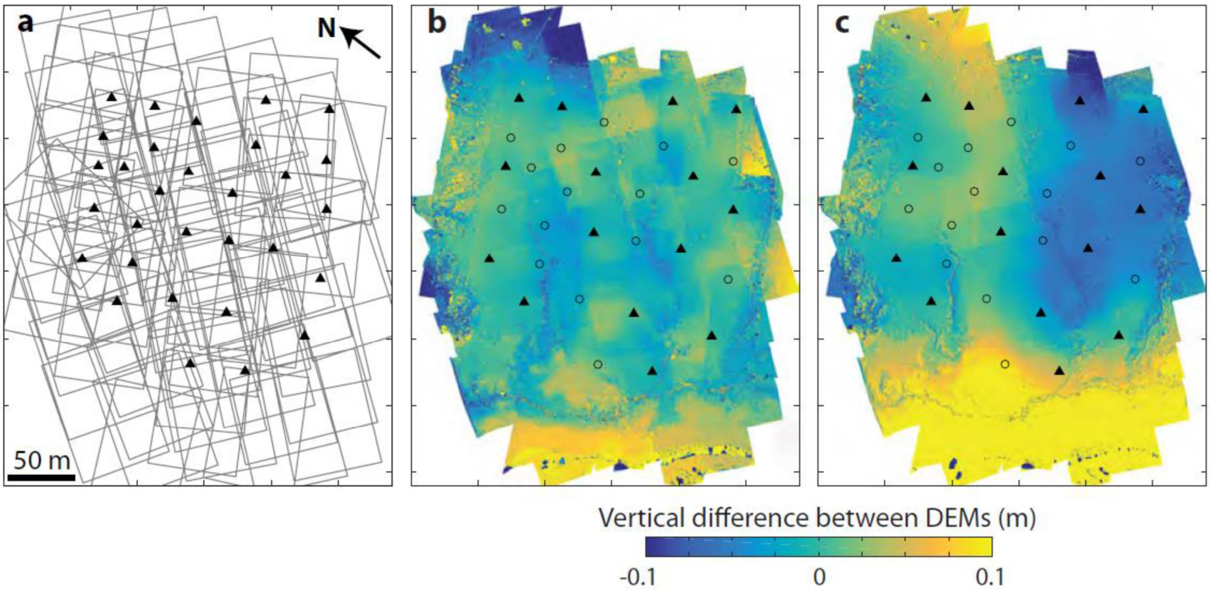


Figure 1: DEM variations resulting from using PhotoScan Pro (v.1.1.6) default or recommended processing settings in a self-calibrating bundle adjustment with the Taroudant survey ('marker accuracy' = 0.5 mm, 'projection accuracy' = 0.1 pixels and 'tie point accuracy = 4.0 pixels; note that default and recommended settings values have changed with more recent software releases). Symbols show 3D ground control points (GCPs), with triangles representing GCPs used for control and circles for GCPs used as check points. ***(a)*** *Planimetric distribution of image outlines in the survey.* ***(b)*** *Vertical differences between two DEMs generated by processing the image set whilst using 15 GCPs as control points, but either with or without the check points present during processing – thus differences represent the effect of the presence of the check points alone.* ***(c)*** *DEM differences when different GCPs are used as control points – one DEM was generated using the GCPs identified by triangles as control points and the circles as check points, the other visa-versa.*

Session 2

Chair: Marc-Henri Derron
University of Lausanne

Terminus Hall

Thursday 11:00 – 12:20, 22nd September

Insights from constant near-realtime laser scanning of actively failing rockslopes

Nick Rosser[1*], Jack Williams[1], Richard Hardy[1], Matthew Brain[1], Graham Hunter[2] & John Davis[3]

[1] *Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK; n.j.rosser@dur.ac.uk*

[2] *3D Laser Mapping Ltd, Ranch House, Chapel Ln, Bingham, Nottingham NG13 8GF,UK*

[3] *Navstar Geomatics Ltd, Riverside Court, Beaufort Park Way, Chepstow, NP16 5UH,UK*

Key words: *rockfall monitoring, near real-time terrestrial laser scanning.*

Understanding the nature of rockfalls and those conditions which promote collapse relies upon detailed monitoring, ideally before, during and immediately after failure. With standard repeat surveys it is rarely the case that surveys coincide with precursors or are contemporaneous with the event itself so gaining insight into the controls on failure and the timescales over which precursors operate remains difficult to establish with certainty. As a result, establishing direct links between environmental conditions and rock-falls, or sequences of events prior to rockfall, remain difficult to define.

Here we present an analysis of a high-frequency long-term dataset captured with a permanently installed 3D laser scanning system developed to constantly monitor an actively failing coastal rock slope. The system is based around a Riegl VZ-1000, integrated with and remotely controlled by 3D Laser Mapping's SiteMonitor4D, and Navstar's GeoExplorer. The system captured data at 0.1 m spacing across > 22,000 m^3 at 30 minute intervals for 9 months. Data is streamed to a server that conducts a rolling analysis of change. In parallel to the development of the hardware, we present a new set of algorithms for differencing that trade temporal resolution against spatial resolution to enhance the precision of change detection, allowing both deformation and detachments to be identified.

From this dataset we present rockfall volume frequency distributions based upon short-interval surveys, the presence and/or absence of precursors, a near-realtime volumetric measurement of rock face erosion, and rockslope response to individual storm events. We also present results from correlations between rockfall and prevailing environmental conditions to define triggering factors for rockfall.

The results hold implications for understanding of rockfall mechanics, but also for the interpretation of data captured using much lower frequency surveys. More details of the system and outputs are available on the project website: http://whitbycoastal.wpengine.com.

Fast surveying of a sea cliff and a landslide based on structure from motion photogrammetry

Giordano Teza[1*], Arianna Pesci[2], Andrea Ninfo[1] & Antonio Galgaro[1]

[1] *Department of Geosciences, University of Padua, Via Gradenigo, 6, I-35131 Padova, Italy; giordano.teza@unipd.it*

[2] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Bologna, Italy*

Key words: *photogrammetry, structure from motion, sea cliff, sailing platform, flying platform.*

Structure from motion (SfM) photogrammetry is increasingly used in geological and geomorphological survey because it allow a fast generation of accurate photorealistic point clouds and digital models in a strongly automated way accessible with the currently available computation resources (WESTOBY *et al.*, 2012; REMONDINO *et al.*, 2014; MICHELETTI *et al.*, 2015).

The simplest approach to SfM is based on free-net Bundle Adjustment (BA) modelling, with an entirely automatic point cloud generation without any constraint. Nevertheless, the resulting point cloud is defined with respect to a non-metric reference frame. To have a metric point cloud, a scale factor (SF) must be introduced. If the coordinates of several Ground Control Points (GCPs), provided e.g. by GPS measurements, are available, the SF and georeferencing of a free-net BA model can be easily obtained. Moreover, some SfM software packages, for example PhotoScan (AGISOFT, 2016), allow the direct incorporation of GCP coordinates into the BA modelling. In this case, a georeferenced point cloud having the correct SF is directly generated. This second approach should be preferred because it leads to better results with respect to the first one.

Sometimes, a very fast survey is necessary because emergency conditions occur. In these conditions, a network of GPSs could be very hard or impossible to be built because of safety reasons and a free-net BA modelling could be the only possible approach to SfM data processing. The SF can be defined by recognizing some points in both the point cloud and in available cartography. Clearly, this simplified procedure implies errors on SF, georeferencing and also in photogrammetric modelling if a large surface is studied.

In order to quantify the error associated to cliff modelling without accurate GCPs, some tests were carried out both in coastal and mountain environment. A ~200 m long, ~60 m high sea cliff located in Monterosso (La Spezia, Ligurian Sea) was acquired by means of a boat-based camera from ~150-m distance and the obtained point cloud was compared with an available model built from laser scanning data (Fig. 1). Several points were recognized in both the free-net point cloud and a map from Google Maps, the corresponding polylines were obtained and the SF was computed as ratio between their lengths. The results show that the correct morphology is reconstructed with ~10 cm accuracy and ~1% error on SF.

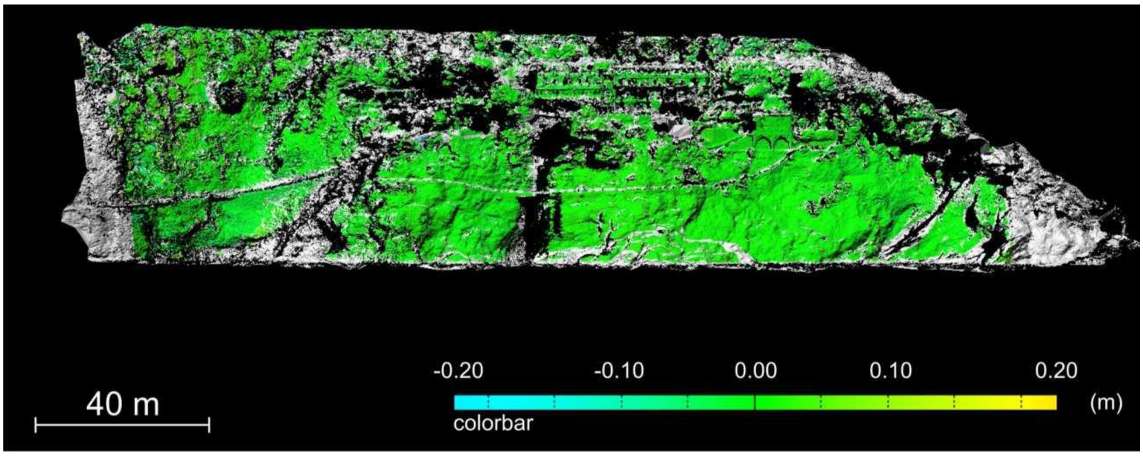


Figure 1:Monterosso sea cliff (La Spezia). Map of differences between the SfM-based point cloud and a model generated with laser scanning data.

The second test was carried out on the Perarolo di Cadore landslide (Belluno, Italian Alps), focusing on an area of ~200 m x 100 m surveyed with a camera based on a Unmanned Aerial Vehicle (UAV) from 20-60 m height (Fig. 2). Nine GCPs, observed by means of rapid-static differential GPS measurements, were available. A free-net BA model was generated without information about the GCPs and then the SF computation and data georeferencing were carried out, therefore simulating a condition where only geographic data are available. The results show that the alignment residual, expressed as standard deviation of the distribution of differences between real and estimated positions of the GCPs (simply used as points for the alignment check), is ~10 cm (and reaches ~50 cm for some images). Instead, if the georeferenced GCPs are incorporated in BA modelling the alignment residual became ~3 cm. Although the accuracy of the final model is significantly better than the initial one, interesting preliminary results can be obtained even if GCPs are unavailable.

In conclusion, the results show that a fast survey, carried out without GCPs, can provide relatively good photogrammetric models that can be used to obtain preliminary but significant information that can be used in emergency conditions to evaluate possible detachments or morphological changes under the condition that their characteristic size is at least ~10 cm.

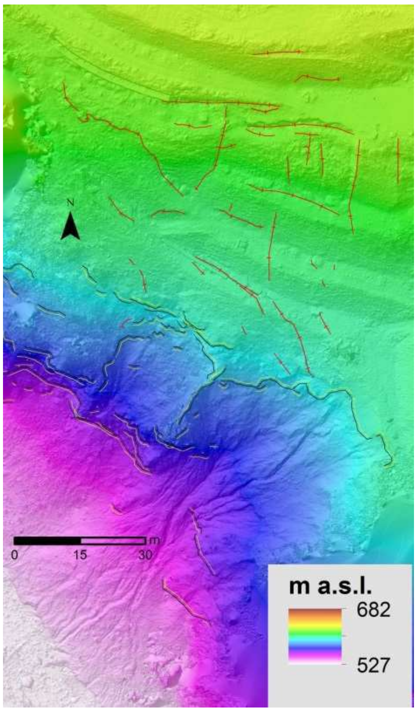


Figure 2: Perarolo di Cadore landslide. Digital elevation model where some morphological features highlighted by free-net BA modelling (edges and fractures) are highlighted.

Acknowledgements: The survey of Monterosso sea cliff was carried out within the framework of the SCANCOAST Project, funded by Regione Liguria and supervised by Cosmo Carmisciano, INGV Roma2. The survey of Perarolo di Cadore landslide was carried out within the framework of the Project “Definizione delle soglie di allertamento del fenomeno franoso della Busa del Cristo in Comune di Perarolo di Cadore (BL)”, funded by Regione Veneto.

References

AGISOFT, 2015. Agisoft PhotoScan web site. Available at: http://www.agisoft.com. [Accessed April 11, 2016].

MICHELETTI, N., CHANDLER, J.H. & LANE, S.N., 2015. Structure from Motion (SfM) photogrammetry. In: *Geomorphological Techniques*, British Society of Geomorphology, London, 2015, http://www.geomorphology.org.uk/sites/default/files/geom_tech_chapters/2.2.2_sfm.pdf. [Accessed April 11, 2016].

REMONDINO, F., SPERA, M.G., NOCERINO, E., MENNA, F. & NEX, F., 2014. State of the art in high density image matching. *Photogrammetric Record*, 29 (146): 144–166.

WESTOBY, M.J., BRASINGTON, J., GLASSER, N.F., HAMBREY, M.J. & REYNOLDS, J.M., 2012. ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179: 300-314.

GB-InSAR and lidar for mapping and predicting slide events in steep terrain

Lene Kristensen[1*], Ingrid Skrede[1], Lars Harald Blikra[1], Gudrun Majala Dreiås[1] & Carlo Rivolta[2]

[1] *NVE, section for Rockslide Management, Ødegårdsvegen 176, 6200 Stranda, Norway; lkr@nve.no*
[2] *Lisalab Ellegi Srl, Via Petrarca 55, I-22070 Rovello Porro, Italia*

Key words: *GB-InSAR, lidar, rock fall, rock slide, snow glide avalanche.*

Failures of large rock slides usually occur after a period of acceleration and increased activity. Monitoring movement makes it possible to predict such failures and issue early warnings (Crosta & Agliardi, 2003). Little is known on the typical development of smaller slide events such as rock falls, rock slides or snow glide avalanches, but it can be assumed that they undergo a similar acceleration phase prior to failure.

A research project in NVE, section for Rockslide Management, focuses on detailed monitoring of rock fall, rockslide and avalanche events in the phase leading up to failure. The goal is to obtain more knowledge of acceleration curves and typical behaviour in natural situations as to improve the early warning and risk management of such events during crisis situations.

Movement is measured by ground based Interferometric Radar – (GB-InSAR) technology, which detects sub-millimetre displacement with a high spatial resolution (Skrede & Kristensen, 2016). On-site data processing and online contact allows for following the development in real-time and constantly adjusting measuring speed to suit the actual velocity. Thus we can limit or avoid data wrapping (fringes) which makes monitoring of large displacements from a satellite-based platform impossible or difficult.

Lidar scans allow for detailed structural analysis of the moving area. NVE uses a Riegl VZ-6000, which measures up to 6 kilometres and is well suited for snow and ice surfaces. Large movement and failure volumes in rockslides may be mapped by repeated lidar scanning. A novel development allows integrating the lidar and GB-InSAR data so the radar displacement data can be shown on a 3D point cloud. This feature is particular powerful when relating displacement to certain geological structures.

Two cases from the project are presented. First is Holmen, Kåfjord, where movements in the autumn 2015 in a $1200m^2$ rock fall release area, 950m asl, led to temporary evacuation of a farm while a protection wall was established. Several acceleration phases occurred prior to a dramatic acceleration on 2nd October as velocities of 60cm/day were reached, followed by several rock falls. However the largest monitored blocks shifted position and regained stability as winter set in. The second case is Stavbrekkfonna, a glide avalanche which most years fails and blocks the fv.63 road, Strynefjellet, Skjåk. A clear acceleration and velocity up to 20m/day was recorded prior to failure on 21/04/2015. The measurements at both sites continued in 2016 and were supplemented with repeated lidar scans.

Our knowledge base is still limited but movement and accelerations probably occur in most slide types prior to failure. Several acceleration phases may occur, and thus the failure time is difficult to predict; however it appears to be possible to determine hazard levels based on the monitoring. For high risk objects, threshold values (most likely site specific) should be determined and evaluated over time.

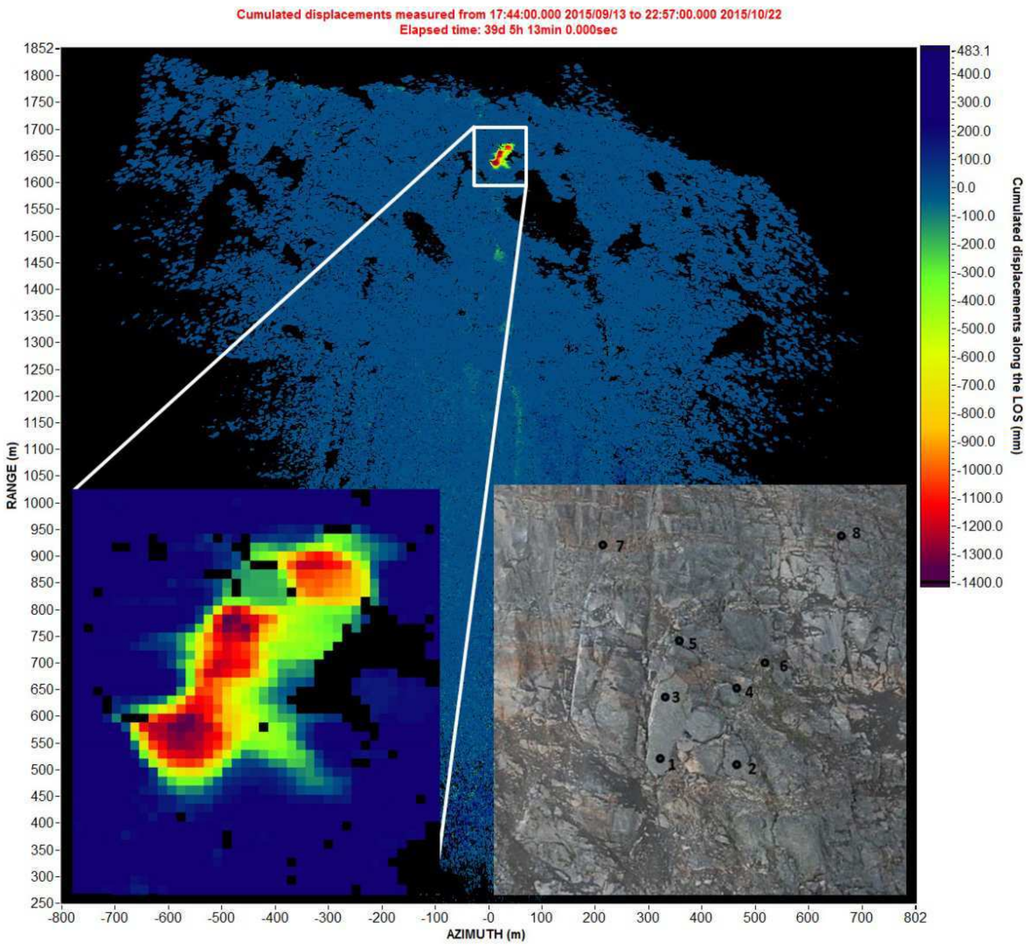


Figure 1: Radar image showing displacement at the Holmen rock fall area and a photo showing approximately the same area with points of time series.

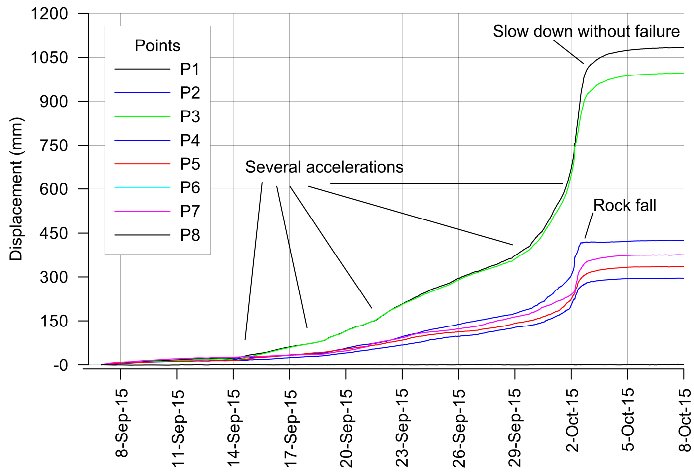


Figure 2: Time series showing displacement measured during the main accelerations at Holmen 2015. Point location shown in Fig. 1.

References

CROSTA, G. B. & AGLIARDI, F., 2003. Failure forecast for large rock slides by surface displacement measurements. *Can. Geotech. J.*, 40: 176-191.

SKREDE, I. & KRISTENSEN, L., 2016. Måling med bakkebasert radar (InSAR) av Stavbrekka, Skjåk kommune. *NIFS rapport*. Norges vassdrags- og energidirektorat.

3D change detection analysis of a coastal landslide performed by multi-temporal point cloud comparison

Giuseppe Esposito[1,4*], Riccardo Salvini[2], Maria Danzi[5], Fabio Matano[3], Marco Sacchi[3], Marcello Seddaiu[2], Renato Somma[4], Umberto Tammaro[4], Claudia Troise[4] & Giuseppe De Natale[4]

[1]Tuscan Earth Sciences PhD program, Centre of Geotechnologies (CGT) - University of Siena, Italy
giuseppe.esposito@unisi.it
[2]Department of Environment, Earth and Physical Sciences and CGT - University of Siena, Italy
[3]Institute for Coastal and Marine Environment (IAMC-CNR), Naples, Italy
[4] Vesuvius Observatory - National Institute of Geophysics and Volcanology, Naples, Italy
[5] Geofotogrammetrica, Via Gemito 3, 80128 Naples, Italy

Key words: *photogrammetry, point cloud, change detection, coastal cliff, landslide.*

The structure from motion (SfM) photogrammetric technique (FONSTAD *et al.*, 2013) has become a suitable method to obtain high resolution topography data in a wide range of geomorphic environments (PASSALACQUA *et al.*, 2015). SfM is designed to reconstruct the three-dimensional geometry of buildings and objects from randomly acquired images, and represents a low cost option respect to traditional photogrammetric and lidar techniques (FONSTAD *et al.*, 2013). In this way, also the 3D geometry of complex natural surfaces can be achieved with a horizontal and vertical accuracy which depend on the choice of sensor for images acquisition, platform (e.g., UAV, boat, vehicle), and method of assignment of geodetic coordinates to the digital data. In advanced geomorphic applications, repeated photogrammetric surveys at different times allow to detect topographic changes in order to map or monitor erosion, deposition and develop sediment budgets.

In this work we present a 3D change detection analysis related to a coastal landslide occurred on 27th October 2013 along the coastal sector of the Campi Flegrei volcanic district, Southern Italy (ESPOSITO *et al.*, 2015). A total of four photogrammetric surveys have been carried out in about two years (Fig. 1), by using a UAV platform for one survey and boats for the other three. In order to accurately define the exterior orientation of images, a topographic survey was also carried out, measuring a series of natural and artificial ground control points external to the landslide area with a long-range Total Station. Images were processed using Agisoft PhotoScan® (http://www.agisoft.com), and 3D point clouds were compared through the "Multiscale Model to Model Cloud Comparison (M3C2)" plugin (LAGUE *et al.*, 2013) included in CloudCompare open source software (http://www.danielgm.net/cc/). The plugin allowed us to estimate orthogonal distances between multi-temporal point clouds as well as uncertainty related to each distance measurement.

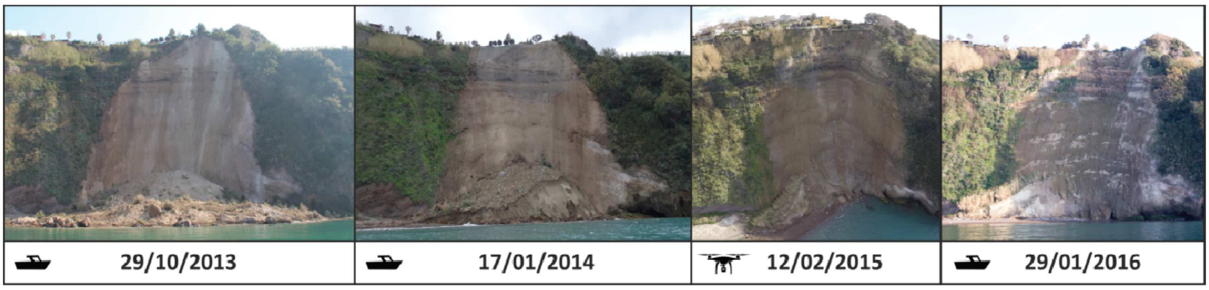
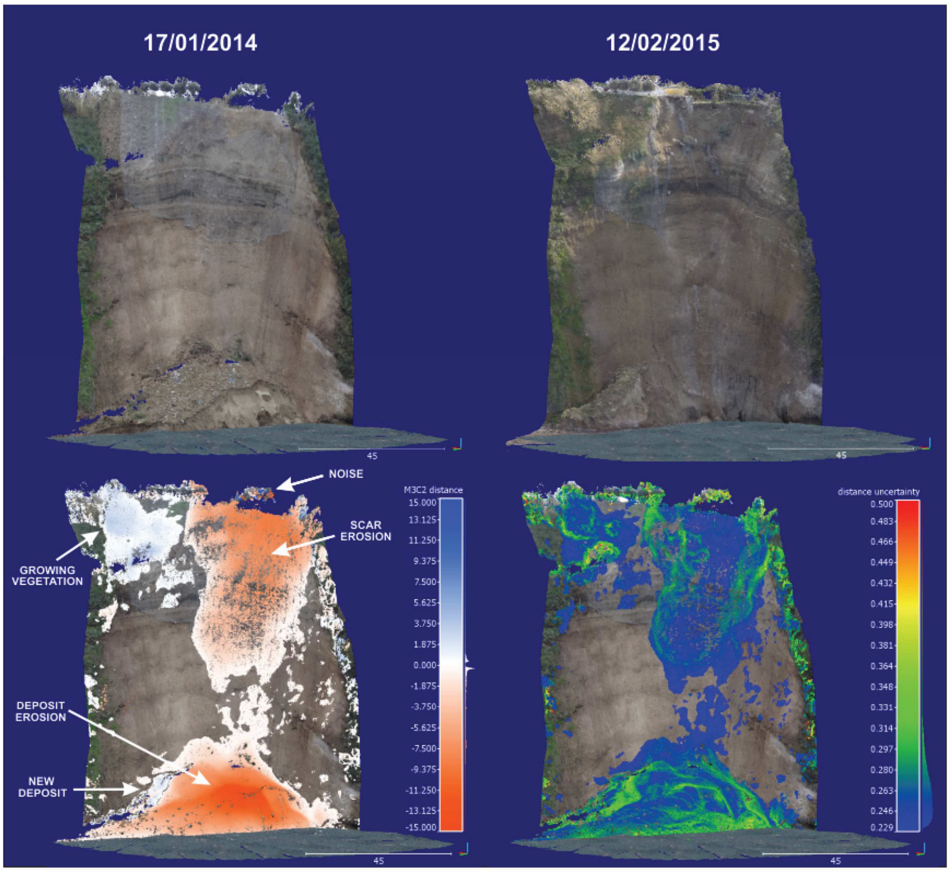


Figure 1: Some images of the landslide captured during the four photogrammetric surveys. Boat and UAV symbols are included to indicate the type of platform used for image acquisition.

SfM processing of each survey resulted in dense point clouds and high-resolution orthophotos. An average co-registration error between clouds was estimated as 11 cm. As output of the M3C2 distance computation we obtained three new clouds in which each point was characterized by distance and uncertainty attributes (Fig. 2). Points corresponding to statistically significant changes were exported and interpolated in ESRI ArcGis® for volume calculation. Volumetric data show that the landslide deposit at cliff toe was progressively eroded by the sea, while landslide scar was affected by a moderate erosion in the first three months after the 2013 landslide event, as well as by a deep erosion between the second and third surveys.

Nevertheless, a negligible eroded volume between 2015 and 2016 surveys was estimated in this area. Deposited sediments decreased through time in the whole landslide area so that, generally, a geomorphic evolution moving towards an equilibrium condition seems to be taking place. The study here described highlights a high potentiality of the SfM and cloud-to-cloud distance computation techniques in geomorphology, both for accurate qualitative and quantitative analysis and for hazard and risk assessment. The studied landslide threats indeed a series of residential buildings located close to the retreating cliff edge.



igure 2: Example of RGB coloured 3D point clouds (top) and M3C2 processed clouds (bottom). Histograms of both stance (bottom left) and uncertainty data (bottom right) from multi-temporal comparison are showed on the right de of the colour scale. White arrows indicate geomorphic features highlighted by the 3D change detection analysis.

:eferences

SPOSITO, G., SALVINI, R., SACCHI, M. & MATANO, F., 2015. A geomatic approach for emergency mapping of shallow

Figure 2: Example of RGB coloured 3D point clouds (top) and M3C2 processed clouds (bottom). Histograms of both distance (bottom left) and uncertainty data (bottom right) from multi-temporal comparison are showed on the right side of the colour scale. White arrows indicate geomorphic features highlighted by the 3D change detection analysis.

References

ESPOSITO, G., SALVINI, R., SACCHI, M. & MATANO, F., 2015. A geomatic approach for emergency mapping of shallow landslides. *Rendiconti Online della Società Geologica Italiana*, 35: 121-123.

FONSTAD, M.A., DIETRICH, J.T., COURVILLE, B.C., JENSEN, J.L. & CARBONNEAU, P.E., 2013. Topographic structure from motion: a new development in photogrammetric measurement. *Earth Surface Processes and Landforms*, 38: 421-430.

LAGUE, D., BRODU, N. & LEROUX, J., 2013. Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (N-Z). *ISPRS Journal of Photogrammetry and Remote Sensing*, 82: 10-26.

PASSALACQUA, P., BELMONT, P., STALEY, D. M., SIMLEY, J. D., ARROWSMITH, J. R., BODE, C. A., CROSBY, C., DELONG, S. B., GLENN, N. F., KELLY, S. A., LAGUE, D., SANGIREDDY, H., SCHAFFRATH, K., TARBOTON, D. G., WASKLEWICZ, T. & WHEATON, J. M., 2015. Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. *Earth Science Reviews*, 148: 174-193.

Session 3

Chair: Roderik Lindenbergh, TU Delft

Terminus Forum

Thursday 11:00 – 12:20, 22nd September

The potential of non-semantic features for UAV remote sensing data fusion

Eduard Angelats[1*], M. Eulàlia Parés[1] & Ismael Colomina[2]

[1] *CTTC, Geomatics Division, Av. Carl Friedrich Gauss 7, Castelldefels, Spain, eduard.angelats@cttc.cat*
[2] *Geonumerics S.L., Av. Carl Friedrich Gauss 11, Castelldefels, Spain;*

Key words: *lidar, photogrammetry, UAVs, sensor fusion, registration.*

Recent advances in UAV platforms together with the miniaturization of cameras and laser scanner sensors make feasible to fly simultaneously, in terms of size and cost, multi-sensor payloads, expanding possible UAV-based applications and targeting new communities. These payloads can consist, for example, of several cameras sensing different spectral bands and/or lightweight, low cost laser scanners. The use of fused data from these sensors can boost the use of UAVs for environmental mapping purposes such as landslide volumetric estimation, biomass estimation or forestry management, to mention a few. In this context, co-registration becomes a key step in order to exploit the complementary characteristics of several cameras and/or laser scanners, and thus generating additional information layers.

The main outputs of these combined systems use to be a set of oriented camera images and 3D point clouds. These point clouds can be derived from a pair of overlapping images or using the laser raw data together with the platform estimated trajectory. Some applications might also require coloured point clouds, which are usually derived from a registration process between camera and laser scanner or, if several cameras are used, from a registration process between all the cameras images.

Nowadays, the standard procedure for camera to camera and camera to laser co-registration requires several steps. The first one is the system calibration, where the lever arm and the boresight between all sensors and the positioning system must be determined. This calibration is usually done by means of a least square adjustment of data acquired specifically for calibration purposes. Note that these values may not be constant and may vary significantly in each mission; these may be even unknown. Thus this calibration step must be done for every mission. Next step is the system orientation. Sensor orientation can be done with direct or indirect approaches and it is usually computed separately for each sensor. Then, it is possible to compute separate point clouds for each sensor. Finally, the derived point clouds are co-registered. This last step is also based in a least squares adjustment and is a complex process with a high computational burden.

The aim of the research presented in this paper is to reduce the aforementioned co-registration steps to a system's boresight calibration problem. In contrast to the standard approach, we propose to solve the orientation and calibration of laser and camera data in a single, combined adjustment. Solving the orientation and calibration allows us to implicitly deal with the co-registration problem. The proposed method is based on the identification of common tie features between images and point clouds and their use in a combined adjustment. In this research we propose to use non-semantic features. By non-semantic features we understand those that provide useful data to solve a certain task but provide no relevant information to describe or understand the scene. Examples of common tie features, used in our approach are basic geometric primitives such as straight line segments, points, planes and ellipses. The parameters to estimate in our new problem will be those describing the features, the orientation and system calibration parameters and the self-calibration parameters. These parameters will be estimated from image coordinates, and raw laser scanner measurements belonging to non-semantic objects extracted from images or point clouds.

The co-registration strategy has been tested using real data from a UAV mapping system including a low cost laser scanner and two COTS cameras. The preliminary results suggest the feasibility and the potential of the approach. The tests show that with the proposed approach co-registration is feasible, cheaper in terms of computational burden and, last but not least, coloured point cloud with high density can be obtained even with low-textured scenes.

An approach for considering beam divergence in voxel space transformation of full-waveform airborne laser scanning data

Nadine Stelling*, Katja Richter & Hans-Gerd Maas

Institute of Photogrammetry and Remote Sensing, Technische Universität Dresden, Helmholtzstraße 10, 01069 Dresden, Germany; Nadine.stelling@tu-dresden.de

Key words: *full-waveform, airborne laser scanning, voxel space, cone tracing, forestry.*

In the past decade, the first commercial full-waveform laser scanning systems have become available. In contrast to conventional laser scanner systems recording several pulses, full-waveform data digitise the entire waveform of the backscattered pulse. Hence, the data provide information about the structure as well as physical backscattering properties of the pulse reflecting matter. Especially in forestry applications, where the emitted laser pulse traverses the vegetation and interacts with tree crowns, full-waveform airborne laser scanning (ALS) data provide a large gain of information for aspects such as a more accurate differentiation of the vegetation structure, biomass estimation or tree species classification. To exploit the full potential offered by full-waveform ALS data and to enable 3D analysis techniques, the conversion of the 1D waveform data in a 3D voxel space representation is essential.

Our work deals with the development of methods for the generation of voxel-based representations of full-waveform ALS data. Instead of extracting discrete points by peak detection, the voxel attributes are derived directly from the amplitudes of the waveform samples. STELLING & RICHTER (2016) specify the required geometric transformations for this purpose and perform an efficient ray tracing approach for the integration of the waveform data into an octree-based voxel representation. Herein, the laser beam divergence is neglected in the first instance, defining an infinitesimally thick ray for each laser pulse from the scanner origin along the direction vector of pulse emission. The attribute of a voxel is derived from the amplitude of the integrated waveform sample. Redundant voxel entries occurring in overlapping areas of different flight strips are considered with the maximum amplitude within a voxel.

To enhance the geometric quality of the volumetric data representation, this contribution will present an advanced approach which includes the laser beam divergence in the voxel traversal process. Concerning this, the ray of laser pulse emission is approximated to be a cone considering the beam spread angle and the scanner origin (Fig. 1). Hence, the waveform samples are represented as circles at their respective distances along the centre axis of the cone. The developed cone tracing method detects occupied voxels by applying the ray tracing approach of (STELLING & RICHTER, 2016) to a bundle of rays describing the cone boundary. In addition, the voxel attributes are obtained considering the fractional coverage of the intersected voxel and the corresponding sample circle.

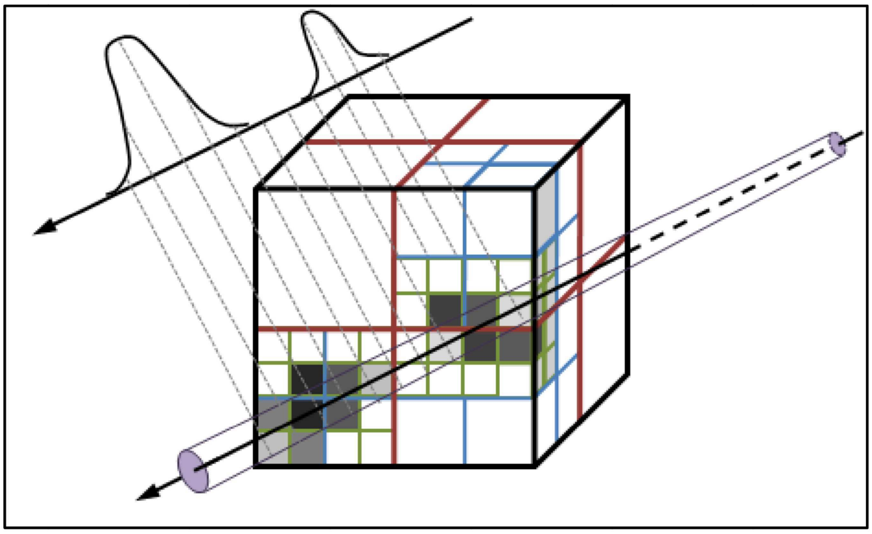


Figure 1: Principle of cone tracing method for converting full-waveform airborne laser scanning data to an octree-based voxel representation.

Furthermore, we present a method allowing 3D filtering directly in voxel space to reduce the number of voxel elements by extracting only relevant object information. The advantage of this approach is that neighbouring waveform information can be considered in the filtering process.

Fig. 2 shows a visualisation of a generated voxel space as well as the corresponding point cloud for comparison reasons. The developed methods will be described in detail and more results will be shown in the presentation.

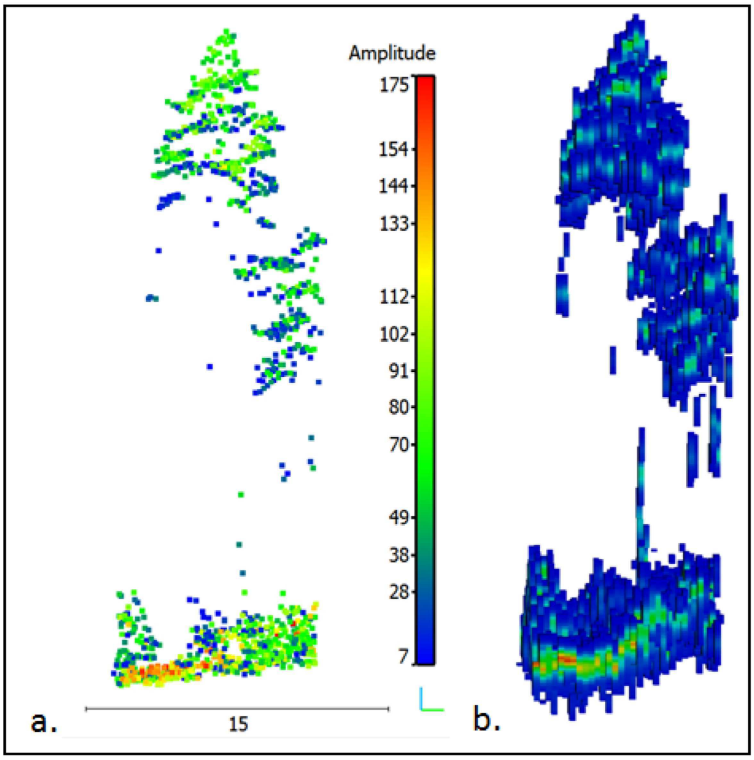


Figure 2: Visualisation of a spruce coloured by amplitude: Point based as result of a Gaussian decomposition (a) and voxel based representation of waveform data (b).

Acknowledgements: The presented work has been funded by German Research Council. We would also like to thank Milan Geoservice GmbH for data acquisition and supply.

Reference

STELLING, N. & RICHTER, K., 2016. Voxel based representation of full-waveform airborne laser scanner data for forestry applications. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B8: 755-762.

Using high-resolution digital surface models for wetland water level assessment

Marko Kohv* & Lii Vammus

University of Tartu, Department of Geology, Ravila 14A, Tartu, Estonia; marko.kohv@gmail.com

Keywords: *structure from motion, monitoring, UAV, photogrammetry, bog.*

Most of the remaining wetlands in Estonia are under European Union level protection but are still threatened by nearby human activity like underground mining in NE Estonia. Accompanying water pumping endangers nearby northern raised bog (MARANDI *et al.*, 2013). Estonian northern raised bogs contain hundreds of small waterbodies – bog pools, which have relatively water levels, usually 0-20 cm below the surrounding bog surface. Bog pools are shortcuts through thick peat layers for water from the bog surface to underlying mineral sediments, mostly fine sand and silt, which are directly drained by nearby oil-shale mines. The first signs of drainage effect should therefore occur in the bog pool water levels, most notably during natural water level minimum in August-September. Mine location at the eastern border of the wetland should cause stronger effect at the eastern side of the wetland compared to the western areas.

Preliminary manual measurements taken in June 2015 did show abnormally low water levels at the eastern side and repeated sUAV surveys were carried out in order to generate high-resolution DSM to assess relative water levels and their changes simultaneously over large number of bog pools. The sUAV was a self-built hexarotor with 24 mb APC-C sensor Sony a6000 on board. Two areas of interest, each approx. 10 ha and containing 70 to 100 bog pools, were photographed from 80 m height. Structure-from-motion software Agisoft PhotoScan was used for 3D point cloud generation and LAStools package for point classification in order to remove tree cover from the DSM. The final DSM was stitched together and smoothed with a median filter in QGIS. It proved to be dense and accurate enough for relative bog pool water level measurements straight from the model itself. Ground control measurements (N=20 for both areas) taken within two days from flights agree well with values derived from the DSM. Model based water level measurements offer at least three to fivefold increase in productivity per man-hour compared with ground measurements alone in hardly accessible landscape like northern bogs. Surface models are archived for possible reanalysis, change detection and verification if necessary.

Reference

MARANDI, A., KARRO, E., POLIKARPUS, M., JÕELEHT, A., KOHV, M., HANG, T. & HIIEMAA, H., 2013. Simulation of the hydrogeologic effects of oil-shale mining on the neighbouring wetland water balance: Case study in north-eastern Estonia, *Hydrogeology Journal*, 21(7): 1581-1591.

Technical aspects related to monitoring riverbank erosion in mountain catchments using point clouds

Marco Scaioni[1,2], Laura Longoni[3,*], Luigi Barazzetti[1], Davide Brambilla[3], Seyereza Hosseini[3], Vladislav I. Ivanov[3], Monica Papini[3], & Eliana Tonelli[1]

[1] *Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, 20133 Milan, Italy*

[2] *College of Surveying and Geo-Informatics, Tongji University, 200092 Shanghai, China*

[3] *Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano, 20133 Milan, Italy; laura.longoni@polimi.it*

Key words: *bank erosion monitoring, close-range photogrammetry, point-cloud processing, river morphology, structure from motion, terrestrial laser scanning.*

In LONGONI *et al.*, (2016) an experimental research about monitoring river erosion on the basis of multi-temporal terrestrial laser scanning measurements has been presented. In this study, a link between weather conditions, river-flow rate and bank erosion has been tentatively established. Indeed, such an investigation had been poorly afforded in the previous literature. The case study consisted in four banks in Val Tartano, Northern Italy. Six data acquisitions over one year were taken, with the aim to better understand the erosion processes and their triggering factors by means of more frequent observations compared to usual annual campaigns. The objective of the research was to address three key questions concerning bank erosion: 'how' erosion happens, 'when' during the year and 'how much' sediment is eroded. The method proved to be effective and able to measure both eroded and deposited volume in the surveyed area. Finally an attempt to extrapolate basin scale volume for bank erosion has been presented.

At the current stage some newly investigated points will be presented and discussed here. In particular, some technical and methodological aspects related to surveying data acquisition and processing are focused. First of all, terrestrial laser scanning (TLS) fully proved to be 'technically' sound for efficient and complete data acquisition, but also revealed some practical drawbacks related to the reduced operational flexibility and transportability, especially in mountain environments. Thus a comparison with structure from motion (SfM) photogrammetry has been accomplished. The goal is to demonstrate with a consistent set of examples that SfM may completely or partially take over TLS. In particular, how to carry out georeferencing of multi-temporal photogrammetric blocks into the same stable reference system is addressed here.

Secondly, the analysis of the 3D point uncertainty in the case of TLS surveying revealed to be a crucial point to understand which eroded or accumulated amount of debris could be statistically detected. Even though several theoretical studies have been published, their follow up on the practice is still not relevant. Here a review of this aspect is reported with the aim to establish guidelines for the practical evaluation of 3D accuracy in the case of point clouds to be used for change detection applications in geomorphological field.

The third last aspect concerns how to compute the surface changes in riverbank point clouds, where in many cases the complex topography may prevent the use of those techniques that are usually applied for comparing 2.5D digital surface models (see SCAIONI *et al.*, 2013; LINDENBERGH & PIETRZYK, 2015). A full 3D method for comparing point clouds is then proposed and the comparison of the results obtained this way with the ones achieved with standard 2.5D techniques is reported.

References

LONGONI, L., PAPINI, M., BRAMBILLA, D., BARAZZETTI, L., RONCORONI, F., SCAIONI, M. & IVANOV, V.I., 2016. Monitoring riverbank erosion in mountain catchments using terrestrial laser scanning. *Remote Sensing*, 8: 241.

LINDENBERGH, R. & PIETRZYK, P., 2015. Change detection and deformation analysis using static and mobile laser scanning. *Applied Geomatics*, 7: 65-74.

SCAIONI, M., RONCELLA, R. & ALBA, M.I., 2013. Change detection and deformation analysis in point clouds. *Photogrammetric Engineering & Remote Sensing*, 79: 441-455.

Session 4

Chair: Luc Girod, University of Oslo

Terminus Hall

Thursday 13:30 – 14:30, 22nd September

Detailed glacier crevasse morphology mapped by helicopter

Christopher Nuth[1*], Luc Girod[1], Jack Kohler[2], Kenneth Bahr[1] & Tor Ivan Karlsen[2]

[1] *Dept. of Geosciences, University of Oslo, 1047 Blindern, Oslo, Norway; christopher.nuth@geo.uio.no*
[2] *Norwegian Polar Institute, Tromsø, Norway*

Key words: *glacier, geoscience, helicopter, SfM, photogrammetry, DEM.*

We produce and analyse a 30 cm resolution Digital Elevation Model (DEM) of the heavily crevassed glacier tongue of Kronebreen in northwest Svalbard. Using a helicopter platform (Eurocopter AS-350), we surveyed the glacier with the ICECAM system (DIVINE *et al.*, in press) that combines a single frequency GPS system with an inertial navigation system (INS) to a standard SLR camera (Canon EOS 5D Mark II) that is mounted on a pole towards the front of the helicopter. The survey acquired ~2500 photographs from about 800 meters altitude covering a ground area of 50 km^2 in 40 minutes at an average flying speed of ~175 km per hour.

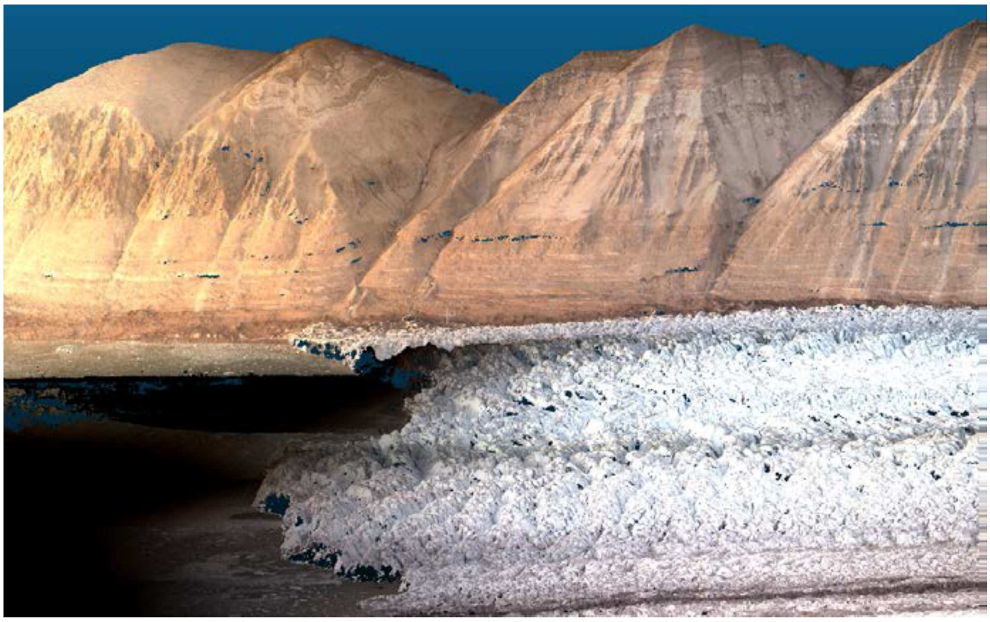


Figure 1: 3D point cloud draped by the imagery over the tongue of Kronebreen.

The single frequency GPS data was post processed using open source software, RTKLIB (TAKASU, 2009), with a base station in Ny Ålesund, about 15 km from the front of Kronebreen, and connected directly to the imagery acquired which marks the GPS epoch for each image in the acquisition log files. Comparisons with post processing results from GAMIT/Track software show a positioning standard deviation of ±30 cm over the course of the flight. We use the free open source photogrammetric suite MicMac (PIERROT-DESEILLIGNY *et al.*, 2016) to generate the DEM without any ground control points (Fig. 1). The imagery and the image positions are used to solve for the camera distortion, INS and leaver arm values. Two strategies for dense matching are performed, per-image-matching and ground-geometry-matching, with the former providing the highest detail and precision within the steep crevasses of the glacier (Fig. 2).

Using the limited outcrop area surrounding the glacier in our survey, we compare our DEM to the most recent product from the Norwegian Polar Institute (NPI) aerial surveying based on flights from 2009. After resampling up to 5 m to match the NPI DEM and subsequent co-registration, the standard deviation of the terrain is about 1.5 m with little bias. This uncertainty reflects the combined precision of the NPI DEM and our upsampled DEM, and thus shows the robustness of our approach with this instrument setup. Moreover, the comparison of the two dense matching strategies showed a standard deviation over the glacier of about 0.70 m and a slight positive bias from the ground-geometry-matching. This reflects mainly the lack of depth the latter DEM achieves within the steep crevasse voids (Fig. 2).

The detailed surface DEM of Kronebreen is of unprecedented resolution which allows for a number of studies related to crevasses within glaciology. For example, crevasse volume and structure along with a number of modelling experiments related to incoming solar radiation and boundary layer meteorology over the rather rough crevassed surfaces of outlet glaciers. The helicopter platform for imagery allows us to acquire data while on other glaciological missions, for example, while measuring the mass balance. The connection with single frequency GPS provides enough precision that we do not require ground control points for accurate bundle adjustments, and our results show an accuracy and precision equivalent with the most precise DEM data available for Svalbard.

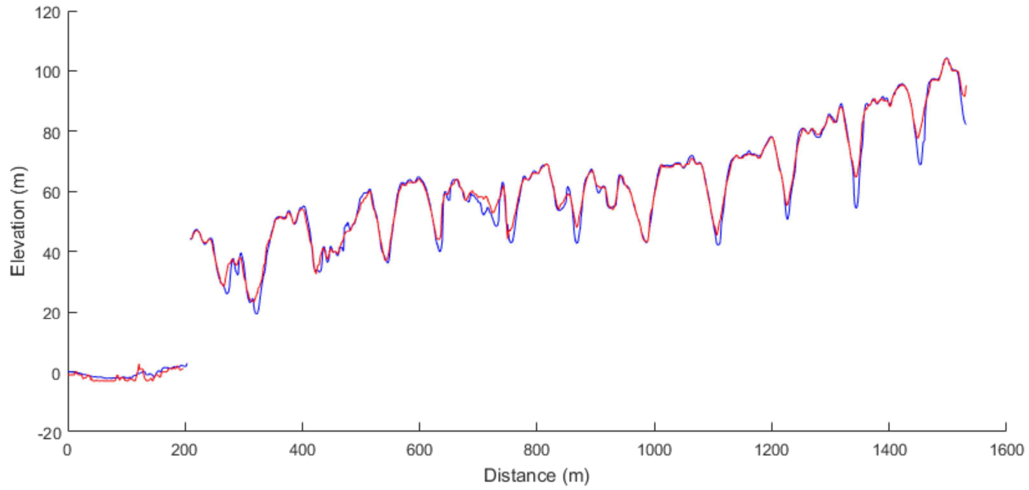


Figure 2: Centre elevation profile of the first 1.5 km of the glacier front. The two dense matching strategies are shown, per-image-matching (blue) and ground-geometry-matching (red).

Acknowledgements: The study was funded by the European Research Council under the European Union's Seventh Framework Program (FP/2007-2013)/ERC grant agreement no.320816 and the ESA project Glaciers_cci (4000109873/14/I-NB). The helicopter and flights were operated for the Norwegian Polar Institute by AirLift AS.

References

DIVINE, D.V., PEDERSEN, C., KARLSEN, T.I., FASTE AAS, H., GRANSKOG, M., HUDSON, S. & GERLAND, S. in press. Photogrammetric retrieval and analysis of small scale sea ice topography during summer melt. *Cold Regions Science and Technology*.

PIERROT-DESEILLIGNY,M., JOUIN, D., BELVAUX, J.,MAILLET, G., GIROD, L., RUPNIK, E.,MULLER, J. & DAAKIR, M., 2016. MicMac, Apero, Pastis and Other Beverages in a Nutshell! http://logiciels.ign.fr/?-Micmac,3-. ENSG, IGN, Champs-Sur-Marne, France.

TAKASU, T. 2009, RTKLIB: Open Source Program Package for RTK-GPS, *FOSS4G 2009*, Tokyo, Japan, November 2, 2009.

Multi-temporal UAV-survey of a calving glacier in Northwest Greenland

Yvo Weidmann*, Guillaume Jouvet & Martin Funk

ETHZ VAW, Hönggerbergring 26, 8093 Zurich, Switzerland;
weidmann@vaw.baug.ethz.ch

Key words: *photogrammetry, geoscience, UAV, glaciology.*

Calving (breaking off of chunks of ice at the glacier terminus) is a major contributor to mass loss of the Greenland and Antarctica ice sheets. To better understand the calving mechanisms, a Swiss-Japanese re-search project monitors the calving front of Bowdoin glacier in Northwest Greenland (78 degrees latitude) since July 2014. During the summer 2015 field campaign, the camera inboard a UAV captured the initiation of a major calving event with 10 cm spatial resolution and a time resolution of 5 days. Two UAV flights were operated prior to and during the opening of a large crack that formed about 100 m upstream from the calving front, propagated laterally over more than a kilometre and eventually collapsed entirely.

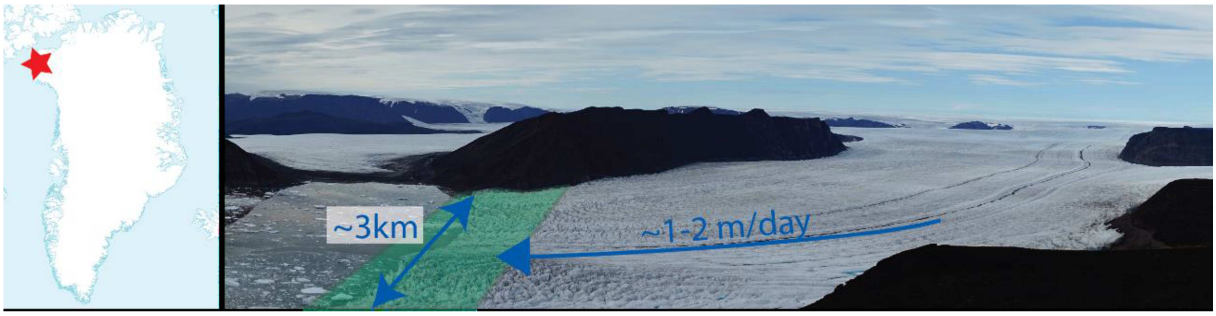


Figure 1: Overview of the calving front of the Bowdoin glacier which was monitored by using UAV (green area).

The choice of the UAV was guided by the following requirements: i) the UAV must be capable of flying autonomously more than 30 km up to 500 m above the ground while carrying a 500 g on-board camera ii) it must be fast and stable to cope with possibly windy conditions iii) the autopilot must be accessible so that problems due to North Greenland conditions can be fixed on site by fine-tuning parameter. A major issue we had to face was the weakness of the magnetic field making the compass unreliable. In the future, this problem could be fixed by changing the way how the orientation is computed in the Pixhawk with APM autopilot.

To achieve the mentioned requirements, the UAV was built based on the commercially available X8-Skywalker airframe and standard components including the Pixhawk autopilot. The X8 airframe provides a reliable and well known base for any kind of scientific instruments. Using a flexible layout of the cargo, the X8 was designed to be flown using 2, 3 or 4 lithium polymer 4S packages. As camera, the mirrorless system cameras of Sony were chosen. The trigger electronic and the camera holder were designed either for APS-C or Full Frame camera bodies with interchangeable lenses. This gives a high level of flexibility for different flight missions and safeness for exchange in case of failures.

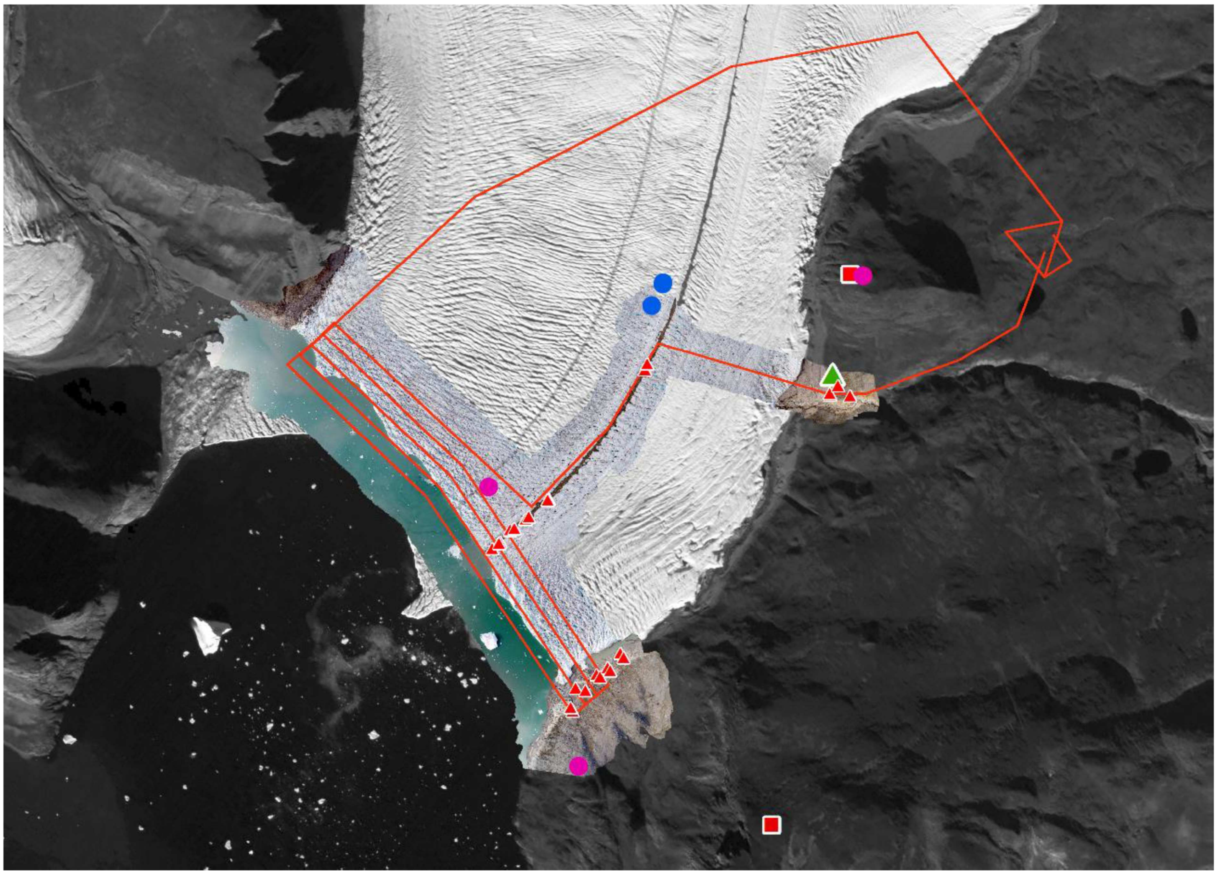


Figure 2: Flight plan (red line) of the calving front monitoring and the DGPS measured Ground Control Points (red triangles).Additionally the locations of seismic arrays (purple dots), the boreholes (blue dots), time laps cameras (red squares) and the camp of the expedition 2015 (green triangle).

For each flight, the UAV acquired about 1000 overlapping pictures of the calving front. Ground Control Points (GCP) next to and on the glacier were installed and measured with Differential GPS (DGPS) to georeference the UAV images. Due to the glacier velocity (more than 1 m/day), the GCPs located on the glacier were measured repeatedly so that their absolute positions at the time of each flight could be determined. The pictures of each flight were post-processed through the software Agisoft PhotoScan to create the digital surface models and ortho-images. High-resolution velocity and strain fields on the surface could be inferred from the ortho-images by feature-tracking techniques, allowing an in-depth fracture mechanical analysis of the calving event.

Is it worth going up there?

Fanny Brun[1, 2*], Patrick Wagnon[1, 3], Etienne Berthier[2], Christian Vincent[1], Camille Réverchon[1], Joseph Shea[3], Philip Kraaijenbrink[4] & Walter Immerzeel[4]

[1] *Univ. Grenoble Alpes, CNRS, IRD, LTHE, UMR5564, Grenoble, France; fanny.brun@ujf-grenoble.fr*
[2] *LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, Toulouse, France*
[3] *International Centre for Integrated Mountain Development, Kathmandu, Nepal*
[4] *Department of Physical Geography, Utrecht University, Utrecht, Netherlands*

Key words: *debris-covered glaciers, Everest, ice cliffs, UAVs, Pléiades, terrestrial photogrammetry.*

Debris-covered glaciers account for more than 10% of the glaciated area in the Pamir-Karakoram-Himalaya (PKH) and are important contributors to the high mountain hydrology in a changing climate. They are also of great interest in terms of glacial hazards (BOLCH *et al.*, 2012). They exhibit a very rough surface and a highly heterogonous debris cover, therefore representing a challenge to remote sensing techniques. Many studies highlighted the potential important role of supraglacial features, such as ice cliffs and supraglacial ponds, and it is therefore important to represent them accurately for process oriented studies (BURI *et al.*, 2016). We studied a small (2.7 km²) glacier of the Nepalese Himalaya, lying above 5300 m asl, using almost concomitant terrestrial photogrammetry (24-28 Nov. 2015), unmanned aerial vehicle (UAV), structure from motion photogrammetry (24-26 Nov. 2015), and tri-stereo Pléiades satellite acquisition (22 Nov. 2015). We focused on two variables of interest in terms of glaciological monitoring: the rate of elevation change for the whole glacier and the ice losses at specific locations, such as ice cliffs or supraglacial lakes.

Our results show that the satellite resolution is high enough to provide a satisfying glacier-wide rate of elevation change, calculated by DEM differencing, and has a better spatial cover than the UAV. The latter misses the highest 4% of the glacier (Fig. 1a), due to complicated access to place ground control points in these very steep slopes (>50°). After adjustments on stable (i.e. off glacier terrain to mimic a case of geodetic mass balance calculation), the median elevation change on glacier is -0.09 m between the UAV DEM and the Pléiades DEM (both resampled at 2 m resolution). The standard deviation of elevation difference between the DEMs is 0.97 m, showing the good agreement between the two DEMs. Nevertheless, the Pléiades DEM shows marked anomalies near cliffs (Fig. 1b and c).

Using the terrestrial photogrammetry data as a reference and working with point clouds and M3C2 algorithm to calculate distances, we show the UAV's ability to represent very steep (even sometimes overhanging) features, such as ice cliffs (see Fig. 2 for an example). While the UAV data are highly relevant for small scale process oriented studies, the satellite imagery is much more suited to calculate glacier mass balances, as it does not require human intervention. The terrestrial photogrammetry can be applied only to small area, due to the extending human means it requires. Nevertheless, the terrestrial photogrammetry remains an always safe acquisition when the UAV is not able to fly, due to strong winds occurring very often at high elevation.

References

BOLCH, T. *et al*., 2012, The state and fate of Himalayan glaciers. *Science*, 336: 310-314.

BURI, P., PELLICCIOTTI, F., STEINER, J., MILES, E. & IMMERZEEL, W., 2016, A grid-based model of backwasting of supraglacial ice cliffs on debris-covered glaciers. *Ann. Glaciol*., 57(71): 199-210.

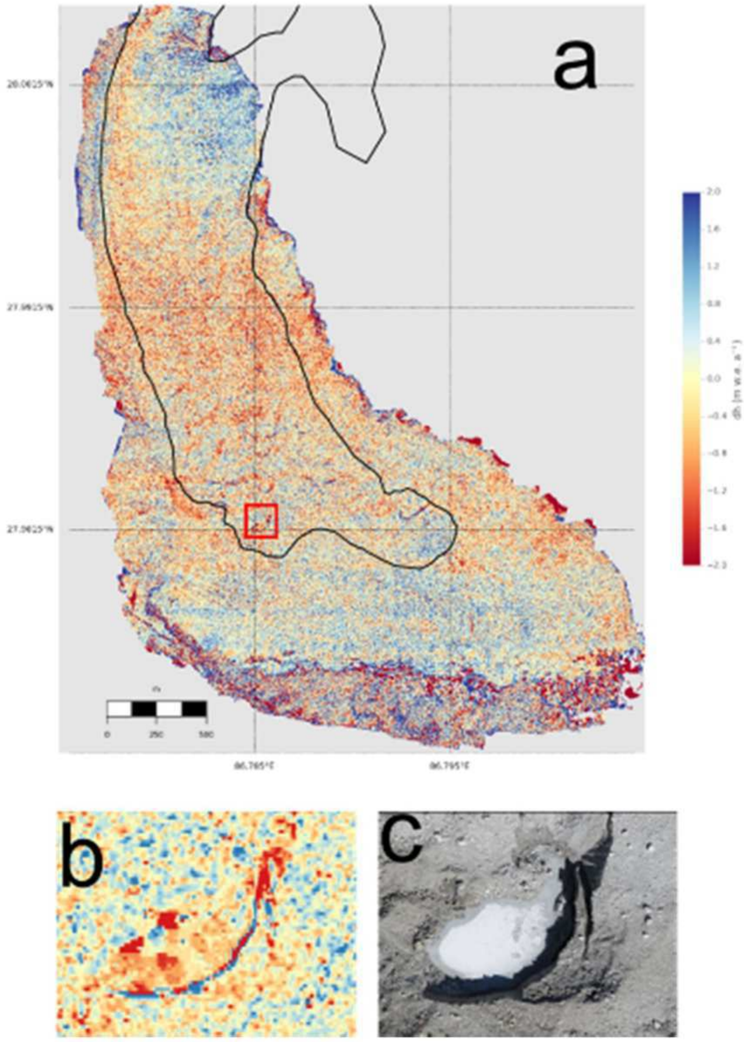


Figure 1: a) Elevation difference of the UAV and Pléiades DEMs acquired less than 5 days apart. The black solid line represents the glacier outline and the red rectangle represents the subset shown in b, c and in Fig. 2. b) Elevation difference around an ice cliff showing the anomalies of the Pléiades DEM. c) UAV orthophoto of the same ice cliff.

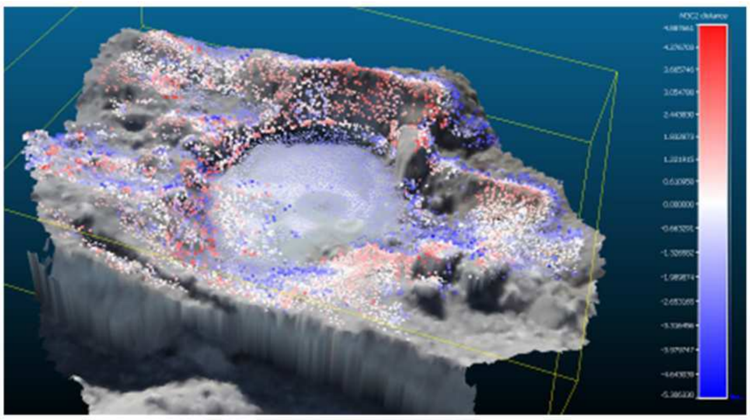


Figure 2: Comparison of point clouds derived from UAV acquisition and terrestrial photogrammetry. Note the offset of the frozen lake.

Session 5

Chair: Mike James, Lancaster University

Terminus Forum

Thursday 13:30 – 14:30, 22nd September

Photogrammetric analysis of lava dome growth using digital photography and thermal imaging: Volcán de Colima 2013-2015

Samuel T. Thiele*, Lauren Schaefer & Nick Varley

Colima Intercambio e Investigación en Vulcanología, Universidad de Colima, av. Universidad 333, Las Viboras C.P. 28040, Colima, México; sam.thiele01@gmail.com

Key words: *lava dome growth, photogrammetry, thermal imaging, Volcán de Colima.*

Photogrammetric and structure from motion (SfM) techniques are increasingly being used to monitor active lava domes (e.g. JAMES & VARLEY, 2012, DIEFENBACH *et al.*, 2013). This study applies SfM techniques to digital single lens reflex (DSLR) and thermal images acquired during observation overflights of Volcán de Colima prior to an eruption and associated dome collapse in July 2015. The collapse triggered a pyroclastic flow which travelled ~10.7km's, threatening several ranches and the town of Quesaría.

Models of the dome were constructed from DSLR and thermal images, and georeferenced by comparison with Google Earth imagery. Models built using DSLR images were found to be substantially more sensitive to degassing and poor lighting, but were of superior quality during favourable conditions. Conversely, models produced from thermal images were less detailed but more robust in non-optimal circumstances. Thermal models were constructed from most flights, while DSLR models could only be built for about 60% of the datasets.

Georeferenced models were exported as triangular meshes and aligned with a pre-dome model to improve relative georeferencing, using MeshLab's iterative closest point algorithm (CIGNONI *et al.*, 2008). Volume differences were then calculated using an implementation of the signed tetrahedron method (ZHANG & CHEN, 2001). In our application of this method, 'regions of interest' are interactively selected and the volume between a reference surface (pre-dome model) and test surface (each dome model) calculated. Hence, the volume of the dome, top portion of the main lava flow, and two reference areas (zero volume change assumed) were estimated (Fig. 1).

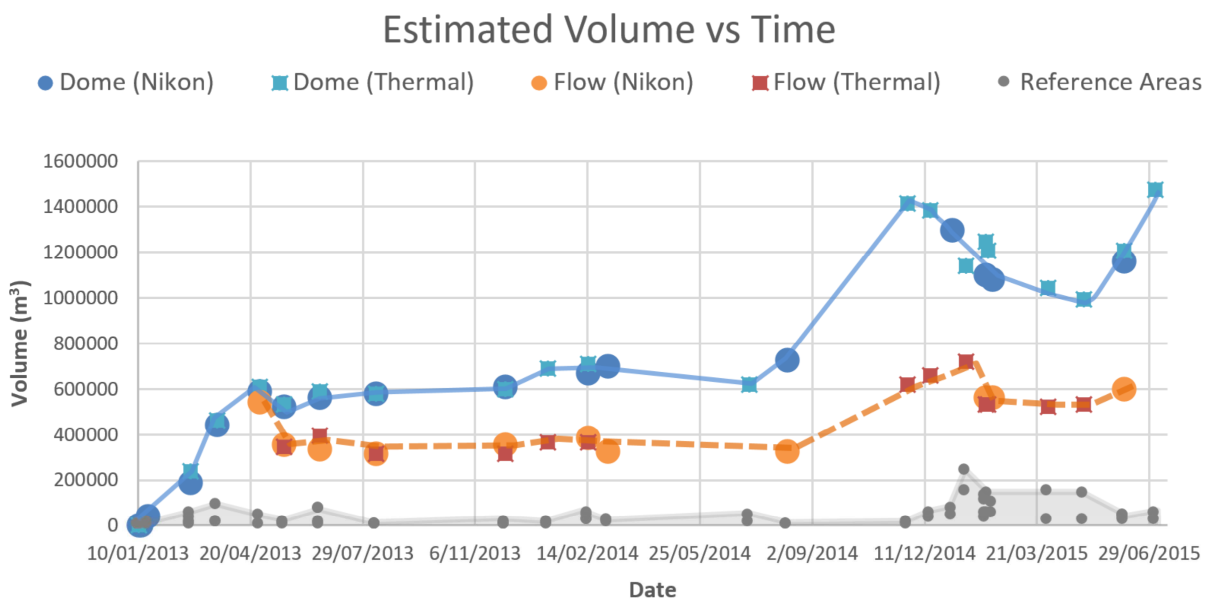


Figure 1: Volume of the lava dome (solid) and lava flow top (dashed) between initiation of dome growth in January 2013 and dome collapse in July 2015. The volume of reference areas (that are not expected to have changed, and hence should equal zero) are shown in grey to give an indication of accuracy. There is generally good agreement between volumes calculated with the DSLR camera (circles) and thermal camera (squares).

Estimations derived from the DSLR and thermal models generally correspond, suggesting (along with low reference area volumes) that they are reasonable, though this method assumes constant underlying topography and hence likely produces underestimates. The data show that dome growth occurred in three distinct episodes.

Between January and April 2013 the dome grew at a rate of ~0.05 – 0.12 m^3/sec, slowly filling the pre-dome crater (Fig. 2a). By late April the crater was overtopped and a lava flow formed on the volcano's west flank, creating a stable configuration where inflow ≈ outflow and dome growth dropped to <0.01 m^3/sec. The second period of dome growth occurred between July and November 2014, growing at ~0.06 m^3/sec (Fig. 2c) and forming several new flows (which accommodated most new lava). The dome then underwent a period of substantial subsidence, deflating at ~0.03 m^3/sec, accompanied by endogenous growth from a second (easterly) vent (Fig. 2c & d). Finally, the dome inflated again (at ~0.05 m^3/sec) from May 2015, before collapsing to the south in early July. Photographic evidence suggests effusion rate may have increased dramatically in the hours preceding collapse.

The geometric and thermal evolution of the lava dome was also examined using the photogrammetric dataset. Most significantly, the models indicate that the July eruption was preceded by effusion from two separate vents (Fig. 2d) and by substantial south directed bulging of the dome. These results suggest that photogrammetric monitoring provides both important insight into volcanic processes and a useful dataset for risk forecasting.

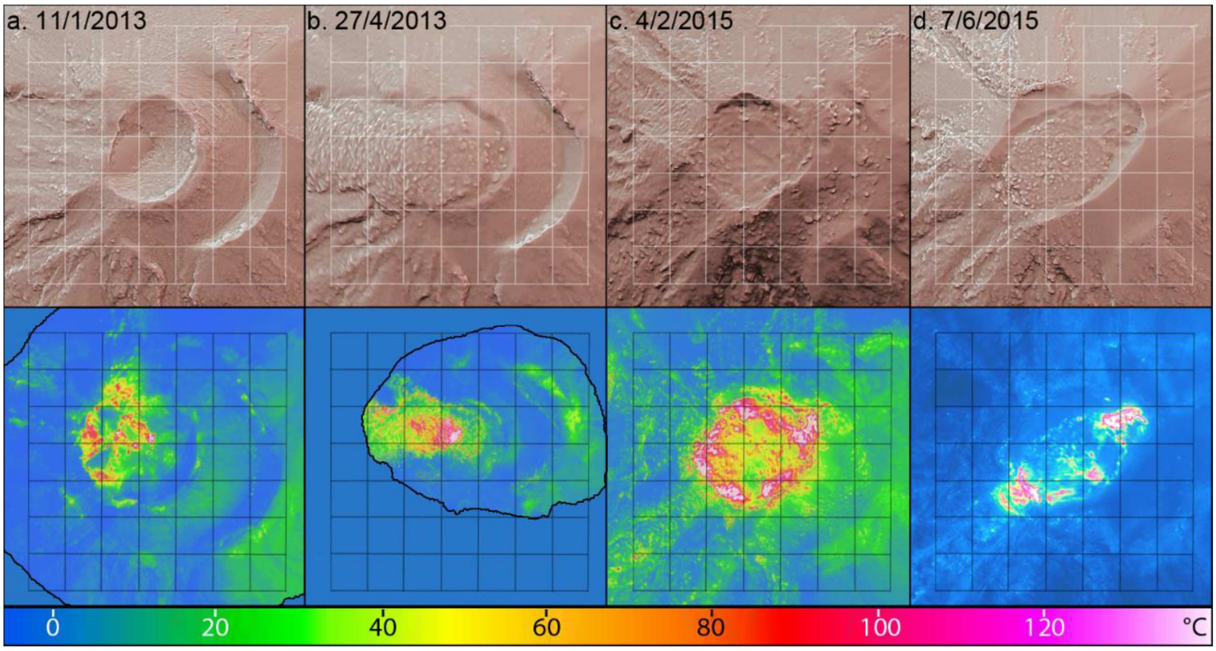


Figure 2: Selected DSLR (top) and thermal (bottom) photogrammetric models demonstrating the evolution of the lava dome between 2013 and 2015 (see text for details). Grid cells are 50×50 meters and oriented NS-EW.

References

CIGNONI, P., CORSINI, M. & RANZUGLIA, G. 2008. Meshlab: an open-source 3D mesh processing system. *Ercim news*, 73, 45-46.

DIEFENBACH, A. K., BULL, K. F., WESSELS, R. L. & MCGIMSEY, R. G. 2013. Photogrammetric monitoring of lava dome growth during the 2009 eruption of Redoubt Volcano. *Journal of Volcanology and Geothermal Research*, 259, 308-316.

JAMES, M. R. & VARLEY, N. 2012. Identification of structural controls in an active lava dome with high resolution DEMs: Volcán de Colima, Mexico. *Geophysical Research Letters*, 39.

ZHANG, C. & CHEN, T. Efficient feature extraction for 2D/3D objects in mesh representation. *Image Processing, 2001. Proceedings. 2001 International Conference on,* IEEE: 935-938.

Laboratory geodesy: Application of open-source photogrammetric software MicMac to monitoring surface deformation in laboratory models

Olivier Galland[1*], Håvard S. Bertelsen[1], Frank Guldstrand[1,2], Luc Girod[3], Rikke F. Johannessen[1], Fanny Bjugger[2], Steffi Burchardt[2] & Karen Mair[1]

[1] Physics of Geological Processes (PGP), Department of Geosciences, University of Oslo, Sem Selandsvei 24, Blindern, 0316 Oslo, Norway (olivier.galland@geo.uio.no)
[2] Centre for Mineralogy, Petrology & Geochemistry, Department of Earth Sciences, Uppsala Universi-ty, Villavägen 16, 75236 Uppsala, Sweden
[3] Department of Geosciences, University of Oslo, Sem Selandsvei 24, Blindern, 0316 Oslo, Norway

Key words: *photogrammetry, analogue models, laboratory geodesy, surface deformation.*

The quantification of deformation is essential in modern laboratory models of geological systems. This paper presents a new laboratory monitoring method utilizing the implementation of the open-source software MicMac, which efficiently implements photogrammetry in structure from motion (SfM) algorithms (GALLAND *et al.*, 2016). Critical evaluation is provided using results from an example laboratory geodesy scenario, magma emplacement (Fig. 1). MicMac automatically processes images from synchronized cameras to compute time series of digital elevation models (DEMs) and orthorectified images of model surfaces. MicMac also implements Digital Image Correlation (DIC) to produce high-resolution displacements maps. The resolution of DEMs and displacement maps corresponds to the pixel size of the processed images. Using 24 MPs cameras, the precision of DEMs and displacements is ~0.05 mm on a 40×40 cm surface. Processing displacement maps with Matlab® scripts allows automatic fracture mapping on the monitored surfaces (Fig. 2). MicMac also offers the possibility to integrate 3D models of excavated structures with the corresponding surface deformation data (Fig. 3). The high resolution and high precision of MicMac results and the ability to generate virtual 3D models of complex structures make it a very promising tool for quantitative monitoring in laboratory models of geological systems.

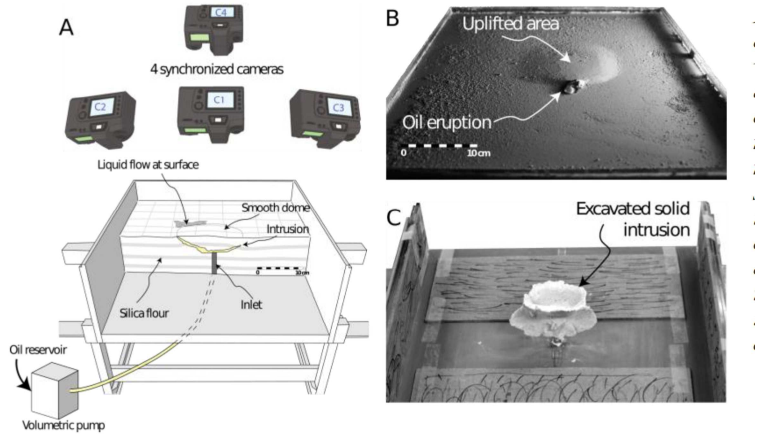


Figure 1: A. Sketch showing the experimental apparatus used for volcano geodesy (see text for explanations). B. Representative oblique view photograph of the model surface during an experiment. The surface exhibited a smooth dome, at the rim of which the oil erupted. C. Representative oblique view photograph of an excavated solidified intrusion. As it is fully excavated, it is possible to apply photogrammetry and compute its 3D shape.

The implementation of MicMac in the laboratory is highly versatile. This laboratory geodesy platform offers significant potential to study numerous geological phenomena involving surface deformation. These processes include tectonics, landslides, glacier dynamics, etc. The ultimate objective is to integrate laboratory data with real geodetic measurements to help interpret natural data, and therefore better constrain the underlying processes.

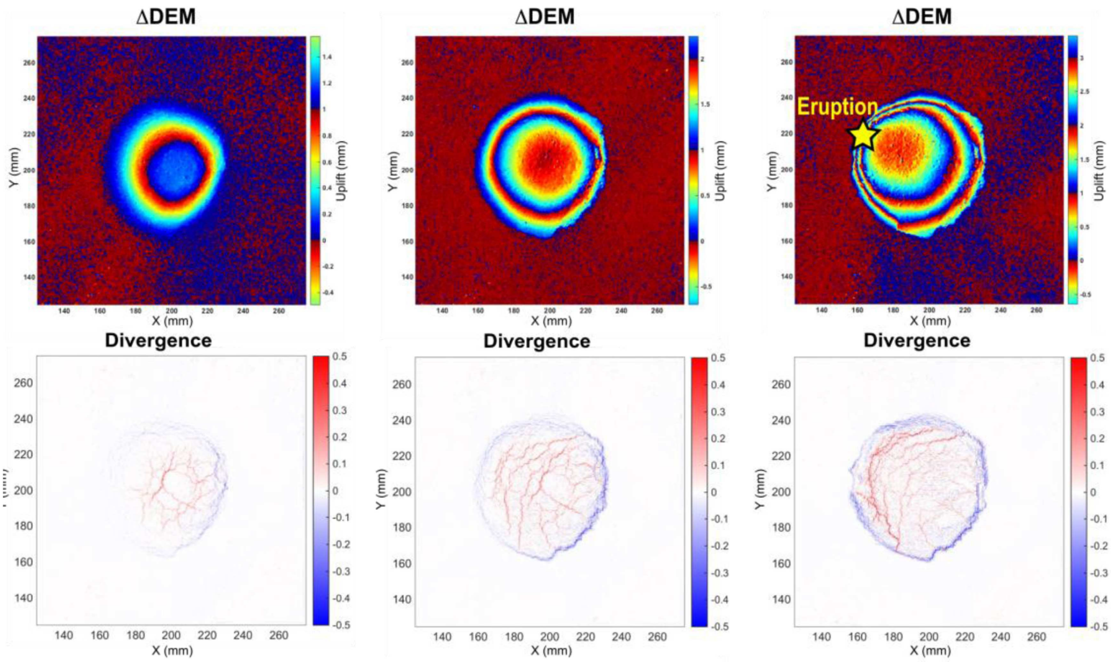


Figure 2: Plots of representative results of the surface evolution during an example magma intrusion experiment at three distinct time steps (columns). The plots display ΔDEM (topography change with respect to initial state), and divergence field calculated from Ux and Uy field. The yellow star locates oil eruption.

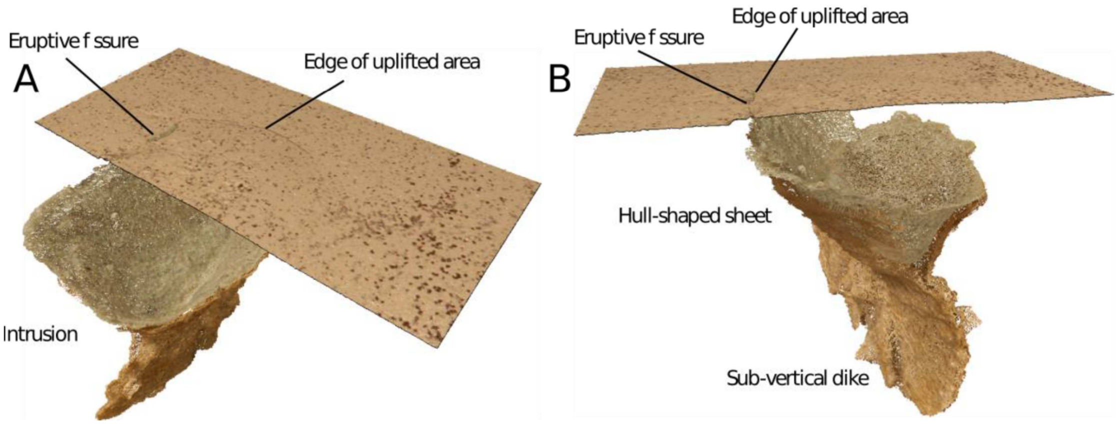


Figure 3: Two representative views of high-density point clouds of part of the model surface after the end of the experiment and the underlying solidified excavated intrusion. Notice the good correspondence between the edge of the uplifted area and the location of the eruptive fissure (recall Fig. 1B).

Acknowledgements: This work was supported by a Centre of Excellence grant from the Norwegian Research Council to PGP (grant no. 146031). Guldstrand's position is funded by the DIPS (Dynamics of igneous plumbing systems, grant no. 240467) project, distributed by the Norwegian Research Council. Girod was funded by the European Research Council under the European Union's Seventh Framework Programme (FP/2007–2013)/ERC grant agreement no. 320816.

Reference

GALLAND, O., BERTELSEN, H.S., GULDSTRAND, F., GIROD, L., JOHANNESSEN, R.F., BJUGGER, F., BURCHARDT, S. & MAIR, K. 2016. Application of open-source photogrammetric software MicMac for monitoring surface deformation in laboratory models. *Journal of Geophysical Research: Solid Earth*, 121, doi: 10.1002/2015JB012564.

Mapping lava flow morphology and structure with unmanned aerial vehicles

Einat Lev*[1], Christopher W. Hamilton[2], Stephen P. Scheidt[2] & M. Elise Rumpf[1]

[1] *Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY USA; einatlev@ldeo.columbia.edu*
[2] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ USA*

Key words: *lava, photogrammetry, volcanology, UAV, structure from motion.*

Lava flows cover vast areas of the rocky planets and moons, including the Earth. Lava flows can have a range of appearances and roughnesses, jointly referred to here as "morphology". Aa and pahoehoe are commonly used terms for describing subaerial lava morphologies, yet they each have several sub-types. When examining a lava flow, whether a fresh, recent one or one that is billions of years old, the surface morphology of the flow can reveal details about the dynamics of flow emplacement, and through that, about eruption conditions. Parameters such as the volumetric effusion rate, lava flow velocity, and the roughness and cohesion of the substrate the lava was flowing over are all important parameters that can be inferred from lava morphology. In addition, the surface roughness of lava flows plays a role as a boundary condition for atmospheric circulation above the lava flow field, and it is thus important to categorize lava morphology.

We present two test cases – one from Chile and one from Iceland – where we recently used unmanned aerial vehicles (UAVs) to collect visible-light images of lava flows, which we then analysed for flow structure and morphology. The two cases span a range of lava viscosity, flux rate, surface roughness and flow thickness, and represent two end-member tectonic environments: a subduction zone, and a mid-oceanic ridge with enhanced hotspot volcanism. Data was collected using a DJI Phantom 3 with built-in camera, and processed using commercial structure-from-motion software (Pix4D and/or Agisoft PhotoScan) to produce orthomosaic images and digital terrain models (DTMs) of the flow surface.

We identify that unique challenges for mapping lava flows using UAVs, including: 1) difficulty accessing interior parts of the flow fields to establish well-distributed ground control points that are geolocated with high precision; 2) operating in harsh weather conditions that are often affected by strong winds, cold temperatures, low atmospheric pressure, and rapidly changing illumination conditions; and 3) challenges associated with charging and maintaining UAV batteries to ensure efficient multi-sortie surveys when favourable weather conditions occur.

Preliminary findings for these test cases are specified below:

1. In Chile, the 1864 eruption of Quizapu volcano generated several >100-m-thick andesitic (SiO_2 content >62%) lava flows that are each >10-km-long. Despite being erupted at the same time and from the same vent, the flows differ in composition and appearance. We used the UAV to examine the details of lateral confinement of each flow, either by existing topography or by self-constructed levees. We are interested in examining how these changed along the length of each flow. In addition to the UAV footage, we collected tens of samples from each flow, and will compare the flow-scale variations with micro-scale variations in chemical composition, crystal content and vesicularity.
2. In Iceland, the 2014–2015 Holuhraun is one of the largest in recent Icelanding history, and has a basaltic composition. The flow exhibits a range of flow morphologies (aa, spiny, and pahoehoe units) related to different eruption phases. Additionally to thickness and volume estimates, we focused our investigation on the morphology along the flow edges, where it is likely to be influenced by interaction with the pre-existing substrate. In addition to characterizing flow morphology, the flow volumes generated from UAV-derived DTMs place important constraints on the thermal budget of the lava flow and the expected durations of hydrothermal activity associated with interactions between the lava and seasonally active glacial melt streams.

Acknowledgements: CWH and SPS were supported by NASA Planetary Geology & Geophysics (PGG) Grant # NNX14AL54G. MER was supported by NSF Postdoctoral Fellowship Grant # EAR-1452748.

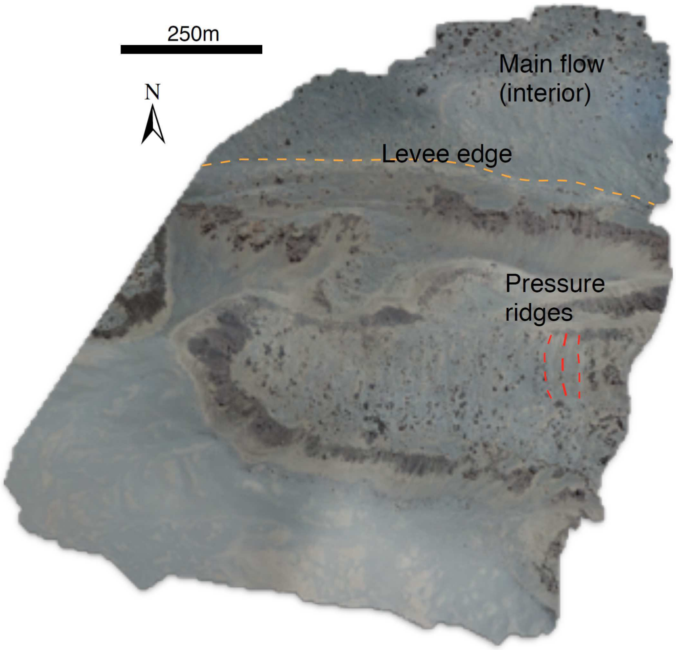


Figure 1: Orthophoto of a lava flow breakout lobe from Quizapu volcano, Chile. The top part shows the edge of the main flow. Pressure ridges are clear on the surface of the breakout lobe. The prominent levee is apparent on the edge of the main flow. The high resolution DTM we will make from this data set will let us constrain parameters of flow evolution and dynamics such as advance rate and cooling rate.

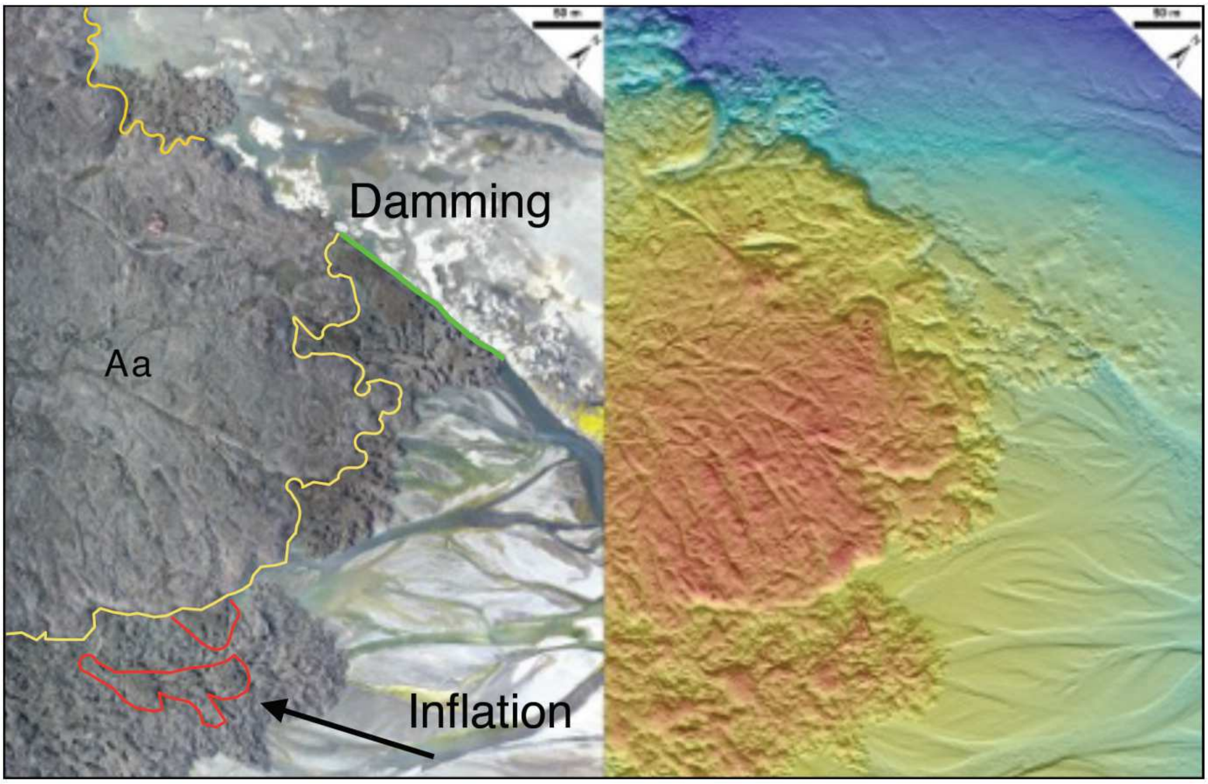


Figure 2: An orthophoto (left) and digital elevation model (right) of the front of the Holuhraun lava flow, Iceland. The image reveals interaction between the lava and the existing topography (e.g., backing up against a high standing linear obstacle), and the braided river system.

Session 6

Chair: Jim Chandler
Loughborough University

Terminus Hall

Thursday 15:00 – 16:05, 22nd September

UAV studies of terrestrial analogs for Martian geology

Jeffrey E. Moersch[1*], Dale T. Andersen[2], Christopher M. Fedo[3], Christopher W. Hamilton[4], Jason G. Muhlbauer[3], Wayne H. Pollard[5], Stephen P. Scheidt[4] & John Taggart[6]

[1] *Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, USA 37996*
jmoersch@utk.edu
[2] *SETI Institute, Mountain View, CA, USA*
[3] *Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, USA*
[4] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA*
[5] *Department of Geography, McGill University, Montreal, Canada*
[6] *Cascade Christian High School, Puyallup, WA USA*

Key words: *UAVs, Mars, terrestrial analogs, photogrammetry, geoscience.*

Background: In the field of planetary science, a “terrestrial analog” is a feature on Earth that has one or more geological, environmental, or biological characteristics in common with features found on another planetary body, or hypothesized to have been present on another planetary body in its past. Good terrestrial analogs share fundamental processes in common with their planetary counterparts, not just an outward physical resemblance. As accessible examples of features found elsewhere in the Solar System, terrestrial analogs may be studied to understand the conditions necessary for their formation, leading to inferences about the conditions that may have been present on other planets. They are also used to test concepts for future spacecraft missions, and to determine the appropriate instrumentation to bring on such missions. It must be stressed that no terrestrial analog is perfectly analogous to its planetary counterpart, but many have key characteristics in common that can illuminate our understanding of other worlds if interpreted in the proper context.

Over the past three years, we have added Unmanned Aerial Vehicle (UAV)-based remote sensing to the set of methods that we regularly employ at our terrestrial analog field sites. Here, we briefly discuss our use of UAVs in campaigns at three different terrestrial analog sites for Mars as case studies that illustrate their utility in this type of work.

The Laki lava flow of southern Iceland: Many of the oldest channel features observed on Mars are unambiguously of fluvial origin, but there are other, younger features called “outflow channels” that are of less certain origin. Outflow channels may be fluvial, having formed through cataclysmic release of groundwater at the surface (over days or weeks), carving the channels in large flooding events. Alternatively, thermal-mechanical erosion by lava may have carved these channels. Discrimination between these hypotheses is complicated by possible overprinting relationships in which lava flows may have resurfaced outflow channels. Further, the hypothesis of channel formation by lava cannot yet be fully evaluated because the literature on lava channels as a general class of feature on any planetary surface is much less well developed than that on fluvial channels.

The Laki lava flow (1783–1784) originated from a series of fissures and “flooded” existing river gorges and the Varmádalur Valley. This valley includes a large, sinuous channel system that extends for tens of kilometres and reaches up to ~20 m in depth, which is comparable in scale to many of the sinuous channels found on Mars. A better understanding of the characteristics of this channel, which is known to have been formed by lava, will inform the debate over the origin of the Martian features. To this end, a field campaign was undertaken in summer, 2015 (HAMILTON *et al.*, 2015), with the goal of using a morphological facies-based approach to understanding the formation and characteristics of the Laki channel. High-resolution UAV-based mapping of the channel was a key component of the work. Over the course of five days of flying, approximately 6000 12-Megapixel, nadir-viewing images of the channel were acquired from a DJI Phantom 3 Professional quadcopter at altitudes of 30 and 100 m above the channel, giving ground sampling distances of ~1 and 4 cm, respectively. Images were acquired in horizontal grid patterns using a beta version of the Pix4D Capture application on a tablet computer to control the UAV. Pix4D Mapper was then used to create digital terrain maps (DTMs) and orthophotos covering approximately 2.2 km^2 (Fig. 1). Geomorphic analyses of these data products are currently being conducted, including precise quantification of the volumes of individual flow units, channel cross-sectional areas, channel slopes, and other parameters needed to constrain flow discharge rates and physical properties such as lava viscosity. Relating changes in lava viscosity along the length of the flow to changes in channel sinuosity and other morphometric properties will provide new insight into the processes by which lava creates channels. Detailed, three dimensional mapping of the flow is also likely to reveal morphologic characteristics that can be used to distinguish lava channels from fluvial channels, which is relevant to the current debate over the origin of sinuous channels on Mars.

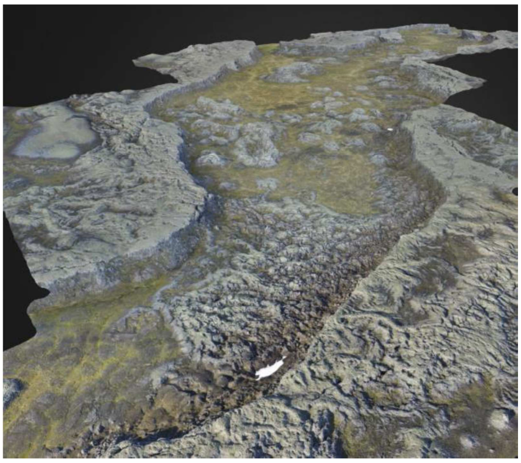


Figure 1: Oblique view of a textured DTM of a portion of the Laki lava channel, Iceland.

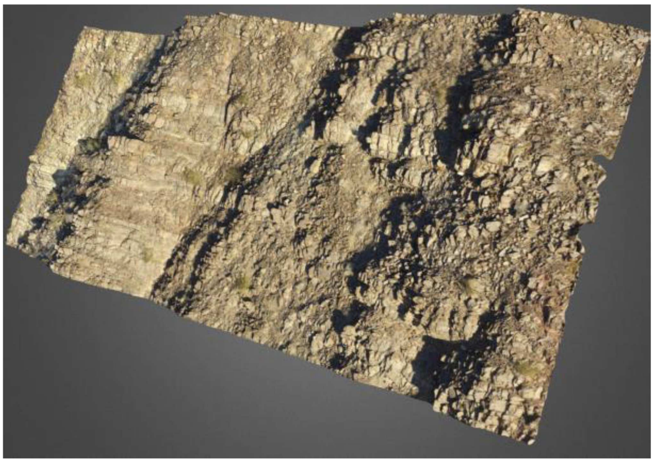


Figure 2: Oblique view of a digital outcrop model of the Wood Canyon Fm (~50m vertical section)

Wood Canyon Fm., Marble Mountains, Southern California: One potentially important style of fluvial sedimentation on the surface of Mars involves the development of braided channel systems, which (on Earth) form when sediment yield is high and vegetation is absent or nearly so. The braided fluvial deposits of the Wood Canyon Formation, in the Mojave Desert of California, are a useful analogue for such Martian environments because they formed prior to the colonization of dry land by rooted plants. Over the course of three days in December, 2015, we used a Phantom 3 Professional to acquire oblique-viewing images of an outcrop of the Wood Canyon Fm, flying in tilted-plane grid patterns at a standoff distance of ~10–15 m. Approximately 2700 images with a ground sampling distance of ~6–7 mm were processed to create a digital outcrop model (DOM) ~50 m high and ~1 km long. We are currently analysing the DOM using the Virtual Reality Geological Studio (www.vrgeoscience.com) to determine palaeocurrent directions from cross bedding and alluvial architecture by defining channel boundaries, which cannot be done on the ground easily because individual channels are extremely wide.

Perennial cold springs, Canadian High Arctic: In July/August 2016, we will conduct field studies of perennial cold springs on Axel Heiberg Island in the Canadian High Arctic. These springs occur in a region with a mean annual air temperature of -15˚C and flow through continuous, 600-m-thick permafrost. It has been suggested (ANDERSEN *et al.*, 2002) that they may be appropriate analogues for sites on Mars where evidence for recent groundwater seepage has been observed. We plan to use a DJI Phantom 4 to provide ~cm-scale DTMs and orthophotomosaics of these features. These products will enable quantitative assessments of the distribution and sizes of the springs. Photogeologic mapping using these products will allow us to determine the specific strata and/or structures that the springs are associated with. Some springs are known to be found in features that have distinctive surface topographic expression, such as pingos and exposed sulphate diapirs (ANDERSEN *et al.*, 2008). The data products provided by our UAV work will allow us to study the control this topography has on the springs. We will also make very low-level (~10 m height) flights over specific springs of interest. The images acquired on these flights will provide mm-scale 3D mapping. This will enable calculation of morphometric properties associated with these springs, such as the volumes of spring mounds composed of precipitates. Some of these spring mounds are composed of ephemeral salts (e.g., hydrohalite) that are thought to partially dissolve during the warm season, so future UAV field campaigns will be used to look for temporal variations in the topography. First-look data products from this work will be shown as part of our presentation.

References

ANDERSEN, D. T., POLLARD, W. H., & MCKAY, C. P., 2008. The Perennial Springs of Axel Heiberg Island as an Analogue for Groundwater Discharge on Mars. *Proceedings of the Ninth International Conference on Permafrost*, Institute of Northern Engineering University of Alaska Fairbanks, Fairbanks Alaska, June 29-July 3.

ANDERSEN, D. T., POLLARD, W. H., MCKAY, C. P. & HELDMANN, J. 2002. Cold springs in permafrost on Earth and Mars. *J. Geophys. Res*., 107(E3), doi:10.1029/2000JE001436.

HAMILTON, C. W., MOERSCH, J. E., & SCHEIDT, S. P., 2015. Applications of unmanned aerial vehicles to the study of volcanic landforms, Paper No. 289-3, *Annual Meeting of the Geologic Society of America*, Baltimore, Maryland.

PRo3D®: A tool for geological analysis of Martian rover-derived digital outcrop models

Robert Barnes[1], Sanjeev Gupta[1], Christoph Traxler[2], Gerd Hesina[2], Thomas Ortner[2], Gerhard Paar[3] & Benjamin Huber[3]

[1] *Imperial College London, United Kingdom; robert.barnes@imperial.ac.uk*
[2] *VRVis Forschungs-GmbH, Vienna, Austria*
[3] *JOANNEUM RESEARCH, Graz, Austria*

Key words: *MSL Curiosity, geoscience, photogrammetry, DOM analysis.*

The key focus on the robotic exploration of Mars for evidence of ancient life is the quantitative characterization of sedimentary rock outcrops that (a) might hold evidence for biosignatures, and (b) provide palaeoenvironmental context to drive the exploration for rocks that have potential to contain biosignatures. Clues to determine ancient sedimentary environments are preserved in sedimentary rock layer geometries, sedimentary structures and textures, and grain size distributions. Rovers are a proxy for field geologists on Mars, taking high resolution imagery of rock formations and landscapes which is digitally analysed in detail on Earth. Panoramic digital cameras (MastCam and Pancam) are used for characterising the geology of rock outcrops along rover traverses. The panoramic camera systems take stereo images which are co-registered to create 3D point clouds of rock outcrops to be quantitatively analysed much like geologists would do on Earth.

As part of the EU FP7 PRoViDE project, we have created a 3D visualization tool called PRo3D that can be used to analyse and directly interpret digital outcrop models. Stereo-imagery derived from Mars rover data can be rendered in PRo3D, enabling the user to zoom, rotate and translate the 3D outcrop model. Interpretations can be digitised directly onto the 3D surface, and simple measurements can be taken of the dimensions of the outcrop and sedimentary features. Dip and strike is calculated within PRo3D from mapped bedding contacts and fracture traces. Measurements and annotations can be organized according to their geological context in a hierarchical way.

These tools have been tested on two case studies from NASA's Mars Science Laboratory Curiosity rover mission The Shaler outcrop in Yellowknife Bay, and the Pahrump Hills field site. Yellowknife Bay and Shaler were visited in the early stages of the MSL mission, and provide excellent opportunities to characterise the transition from lacustrine to fluvial conditions on ancient Mars. The Pahrump Hills were visited by the MSL Curiosity rover between Sols 753 and 904 of operation, and was the location for the first multi-pass, detailed geological campaign of the mission, at the base of Mount Sharp. A fluvio-deltaic-lacustrine succession was identified in this locality, together with strong evidence of diagenetic imprints. Future work will test the validity of geological measurements taken from digital outcrop models of mar-tian outcrops by comparing stereo data collected by panoramic camera emulators with in situ field measurements on terrestrial outcrops.

Representative examples and further information about the interactive 3D visualization tool can be found on the FP7-SPACE PRoViDE Project web page http://www.provide-space.eu/interactive-virtual-3d-tool/.

Acknowledgements: The research leading to these results has received funding from the European Un-ion's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 312377 "PRoViDE".

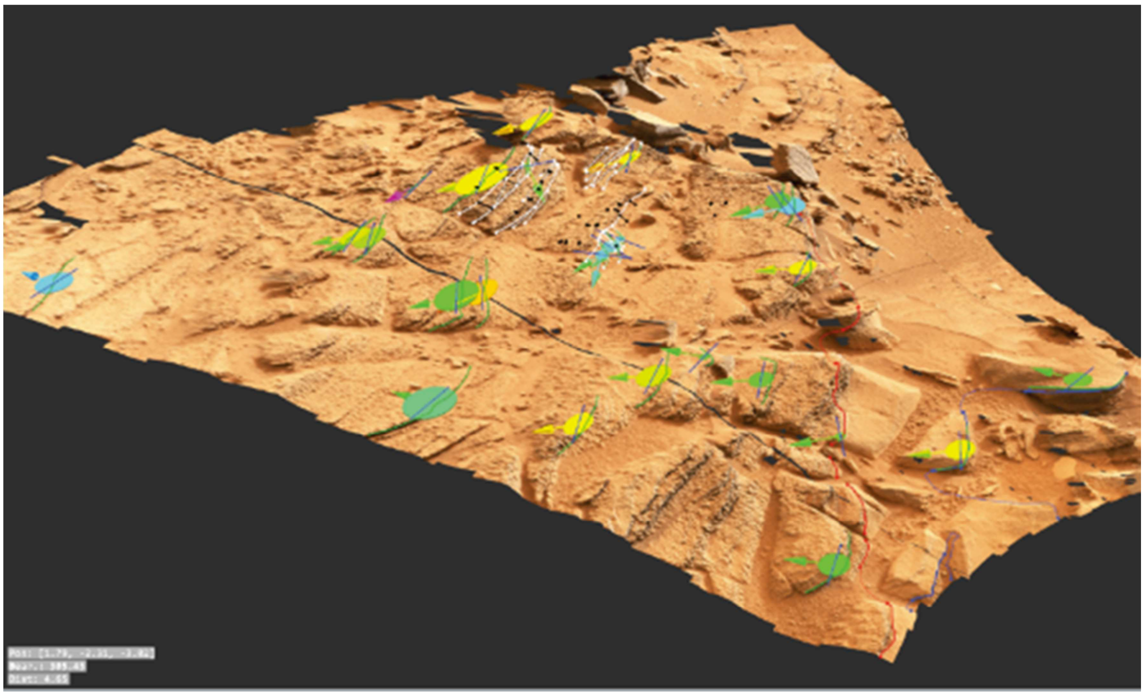


Figure 1: Pro3D interpretation of the stratigraphy at Shaler (imaged on Sol 318), showing the main stratigraphic boundaries as red and blue lines, bedset boundaries as thick white lines, and laminations within those bedsets as the thin white lines. The dip and strike values are colour coded by dip value, and dip 15° - 20° to the southeast, however, this requires validation. The findings show that the outcrop represents a fluvial environment, with recessive, fine grained units interlayered with coarse, pebbly units. The outcrop captured in this reconstruction is 5.6 m in length and 5.9 m across at the top of the image.

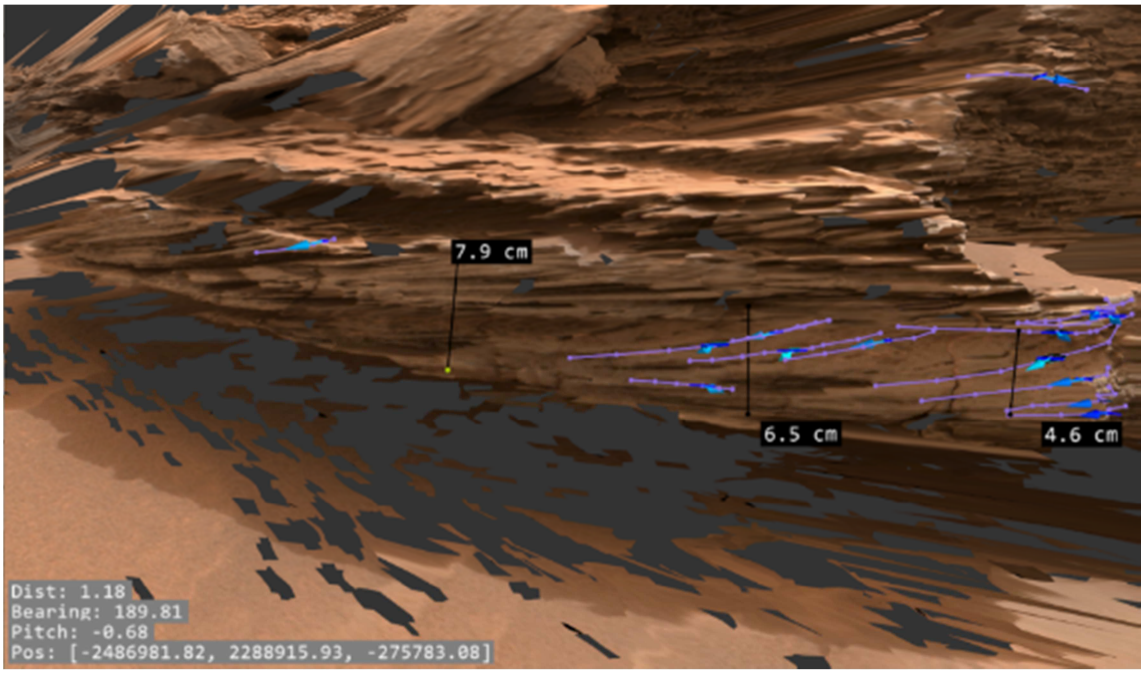


Figure 2: Measurement of the dip (purple lines) and thickness (black lines) of fluvial cross laminated fine sandstone bedsets at Whale Rock, Pahrump Hills. This dataset was imaged on Sol 796.

Listening to 3D topography data with interactive sonification

Karen Mair[1*] & Natasha Barrett [2*]

[1] *PGP - Department of Geosciences, University of Oslo, Oslo, Norway; karenmair@geo.uio.no*
[2] *Department of Musicology, University of Oslo, Oslo, Norway: nlb@natashabarrett.org*

Key words: *Sonification, auditory display, photogrammetry.*

In this presentation we demonstrate how interactive spatial sonification can be used as an auditory display for 3D topographical data. We sonify high-resolution virtual outcrop data obtained by structure from motion photogrammetry of UAV based images (GALLAND *et al.*, 2016).

Figure 1: Field outcrop of a volcanic sill intruded into shales at Las Loicas, Argentina forms the basis of the data tested in this presentation

Sonification is a technique to map data with sound, and has the potential of revealing information to our aural rather than visual senses. The approach we use applies parameter mapping sonification, featuring spatial audio, and is currently implemented in an application called 'Cheddar' (BARRETT, 2016). Cheddar sonifies data in real-time, where the user can modify a variety of temporal, spatial and sound parameters during the listening process, and thus more easily uncover patterns and processes in the data than when applying non-real time, and thus non-interactive techniques. Further, by engaging a 360-degree auditory perceptual experience, the user can detect information that may not be apparent to the eye.

Figure 2: Demonstrating the interactive parameter mapping sonification tool 'Cheddar'.

In previous science-art collaborations (e.g. BARRETT & MAIR, 2014), we applied Cheddar as an auditory display for geological datasets describing 3D geometric features that temporally evolve during the course of the model or process. In this, our latest work, we apply these techniques to 3D digital elevation models where instead of a temporal process per se, we display transects or thin slices through the dataset. The timeline of the sonification thus reflects movement along the slice. Details such as colour variations and topography that reveal fracturing, veining, geometrical relations and topographic relief can be interactively explored in real time.

Acknowledgements: We thank Olivier Galland (University of Oslo) for providing unpublished virtual outcrop field data (GALLAND *et al.*, 2016). Fieldwork was supported by Norwegian Research Council and YPF

References

BARRETT, N., 2016. Interactive spatial sonification of multidimensional data for composition and auditory display. In press: *CMJ*, 40:2

BARRETT, N., & MAIR, K. 2014. Aftershock: A science–art collaboration through sonification. *Organised Sound*, 19(1).

GALLAND, O., BERTELSEN, H.S., GULDSTRAND, F., GIROD, L., JOHANNESSEN, R.F., BJUGGER, F., BURCHARDT, S. & MAIR, K. 2016. Application of open-source photogrammetric software MicMac for monitoring surface deformation in laboratory models. *Journal of Geophysical Research: Solid Earth*, 121, doi: 10.1002/2015JB012564.

Session 7

Chair: Thomas Dewez, BRGM – French Geological Survey

Terminus Hall

Friday 8:30 – 10:15, 23rd September

Exfoliation sheets detection with terrestrial laser scanning and thermal imaging (Yosemite Valley, California, USA)

Antoine Guerin[1*], Marc-Henri Derron[1], Michel Jaboyedoff[1], Antonio Abellán[1], Olivier Dubas[1], Brian D. Collins[2] & Greg M. Stock[3]

[1] *Risk Analysis Group, University of Lausanne, Lausanne, Switzerland, antoine.guerin@unil.ch*
[2] *United States Geological Survey, Landslide Hazard Program, Menlo Park, California, USA*
[3] *National Park Service, Yosemite National Park, El Portal, California, USA*

Key words: *lidar, infrared thermography, rockfall, exfoliation, deformation, monitoring.*

Rockfall activity in Yosemite Valley is often linked to the presence of sheeting joints (i.e., fractures separating exfoliation sheets), parallel to the topography and ubiquitous throughout the valley (MARTEL, 2011). The Yosemite rockfall database (STOCK *et al.*, 2013) shows that many historical events occurred without recognized triggers, during warm and dry periods, raising the possibility that daily temperature variations were involved in triggering of rockfalls. However, little is known concerning the impact of thermal stresses on rock face deformation, despite its occurrence at all times of year. To fill this gap, we carried out several experiments in October 2015: (a) We first monitored a sub-vertical granodiorite flake for 24 consecutive hours using lidar, crackmeters and infrared thermal sensors; (b) We monitored a rockwall composed of tens of exfoliation sheets for eight hours (from 17h30 to 01h30) with lidar and thermal imaging; (c) We fixed our thermal imager on a GigaPan device to take sequences of thermal panorama during rock cooling and at the scale of cliffs like El Capitan (~1000-m-tall).

The lidar monitoring of experiment (a) allowed quantifying one full contraction-expansion cycle of the monitored sheet, confirming the results of COLLINS & STOCK (2016). During this experiment, the maximum crack closure (-4.9 +/- 0.5 mm) occurred around 08h00 (Fig. 1), following a 40 minutes delay of when surface temperatures were minimum. This deformation value is consistent with the one measured by the crackmeter C5 (-5.33 +/- 0.01 mm), located where the crack aperture is the largest (14.8 cm). The thermal pictures were then compared to each other to quantify the thermal behaviour of the flake during cooling and warming periods. The results show that during the night, this is the central part of the sheet which undergoes the most significant cooling. Conversely, this is the flake edge which undergoes the most significant diurnal temperature variations.

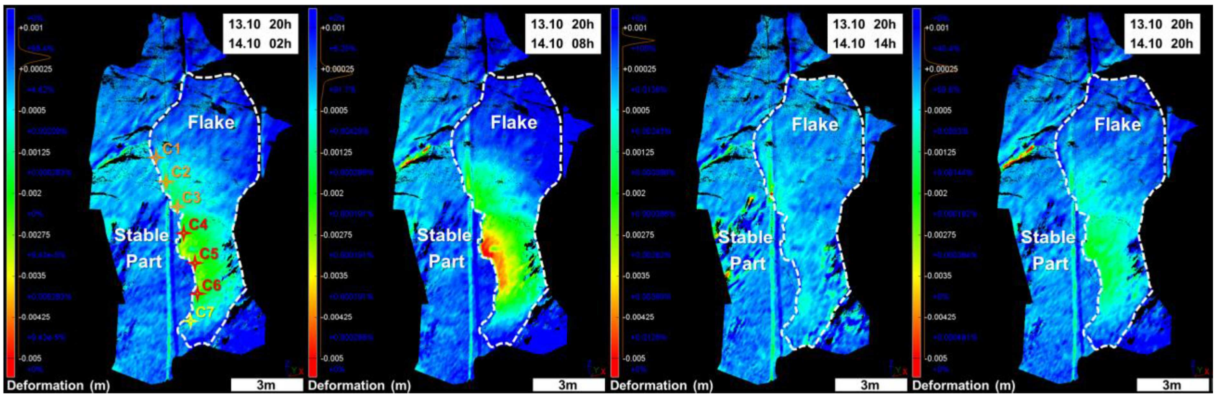


Figure 1: Daily deformation of the granitic exfoliation monitored from ground-based lidar at 02h00, 08h00, 14h00and 20h00 on 14 October 2015 compared to 20h00 on 13 October 2015. C1 to C7 indicate the location of crackmeters (standard analog comparators with springs). Orange crackmeters: range +/- 0.5 mm; Red crackmeters: range +/- 12.5 mm; Yellow crackmeter: range +/- 2.5 mm. The dashed white line shows the flake limits.

With the experiment (b), we detected negative deformations (contraction) for the flakes whose crack are persistent and apertures greater than 9 cm. In this experiment, we observed also that it is the central part which undergoes the most significant nocturnal cooling and this does not depend on the length of the exfoliation sheets (Fig. 2), which varies in this experiment from a few dm to several m. Finally, the comparison of thermal panoramas of experiment (c) shows that the cooling amplitude varies depending on lithologies: the cooling seems more important for dark rocks (e.g., diorite) than for light-coloured rocks (e.g., granites) which reflect more incident radiation (Fig. 2).

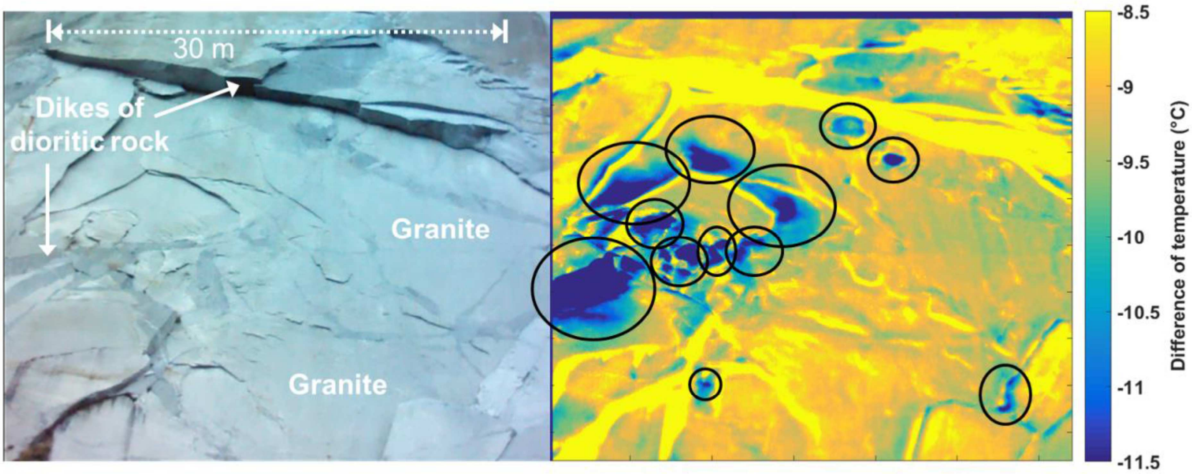


Figure 2: Mapping of exfoliation sheets (black circles) located in the rockwall monitored for the experiment (b). Left: front view of the rockwall situated in the southeast face of El Capitan. Right: cooling of the rockwall between 17h30 on 19 October 2015 and 01h30 on 20 October 2015.

Our experiments indicate that the coupling of lidar and thermal imaging provides very interesting information about the process of cyclic daily thermally driven deformation of partially detached exfoliation sheets. Furthermore, the thermal comparisons show that the infrared thermography can be used to remotely detect some flakes in a cliff and thus help drawing a 3D map of exfoliations sheets. Nevertheless, several thermal corrections are still needed in order to well take into account the influence of the incidence angle, the emissivity and reflective temperature on the measurement recorded by thermography.

Acknowledgements: The authors would like to acknowledge the Swiss National Fund (200020_159221) and the National Park Service at Yosemite National Park for supporting this research.

References

COLLINS, B.D., & STOCK, G.M., 2016. Rockfall triggering by cyclic thermal stressing of exfoliation fractures. *Nature Geoscience*, 9: 395-400.

MARTEL, S. J., 2011. Mechanics of curved surfaces, with application to surface-parallel cracks. *Geophysical Research Letters*, 38(20): L20303.

STOCK, G.M., COLLINS, B.D., SANTANIELLO, D.J., ZIMMER, V.L., WIECZOREK, G.F., & SNYDER, J.B., 2013. Historical rock falls in Yosemite National Park, California (1857-2011). *US Geological Survey Data Series*, 746.

Simulated full-waveform laser scanning of outcrops for development of point cloud analysis algorithms and survey planning: An application of the HELIOS lidar simulation framework

Sebastian Bechtold, Martin Hämmerle* & Bernhard Höfle

Department of Geography, GIScience, Heidelberg University, Heidelberg, Germany;
haemmerle@uni-heidelberg.de

Key words: *laser scanning, lidar, outcrop modelling, simulation, 3D geoinformation.*

3D point clouds are of high value for geosciences because they can be used to model and examine complex geometries in 3D (e.g. overhangs or crevasses). A common method for producing 3D point clouds is lidar or laser scanning, comprising a variety of sensor configurations and platforms. Taking lidar measurements in the field may not be feasible or of advantage for certain studies such as the testing of point cloud processing algorithms. However, to develop and test algorithms for 3D geodata processing, training datasets play a crucial role (PICKEL *et al.* 2015).

We present a highly flexible open source laser scanning simulation framework named HELIOS (BECHTOLD & HÖFLE 2016). Due to its modular software architecture, HELIOS can support a wide range of projects in laser scanning research for geoscience applications. It can be used to simulate many different types of laser scanners, as well as terrestrial, mobile and airborne scanning platforms. In contrast to many other laser scanning simulators that are based on '2.5D' elevation raster terrain, HELIOS uses full-3D triangle meshes and/or voxels to represent the geometry of the scanned environment (Fig. 1). This opens up the possibility to simulate laser scanning with high realism, such as of rock outcrops including cracks and overhanging parts, caves, vegetation, and so forth.

Virtual outcrop scenes for scanning simulation can be created in two ways: One option is to use realworld data that was acquired with a real laser scanner or photogrammetrically. Alternatively, purely artificial scenes can be created with procedural scene generation algorithms, or through manual construction using 3D modelling software.

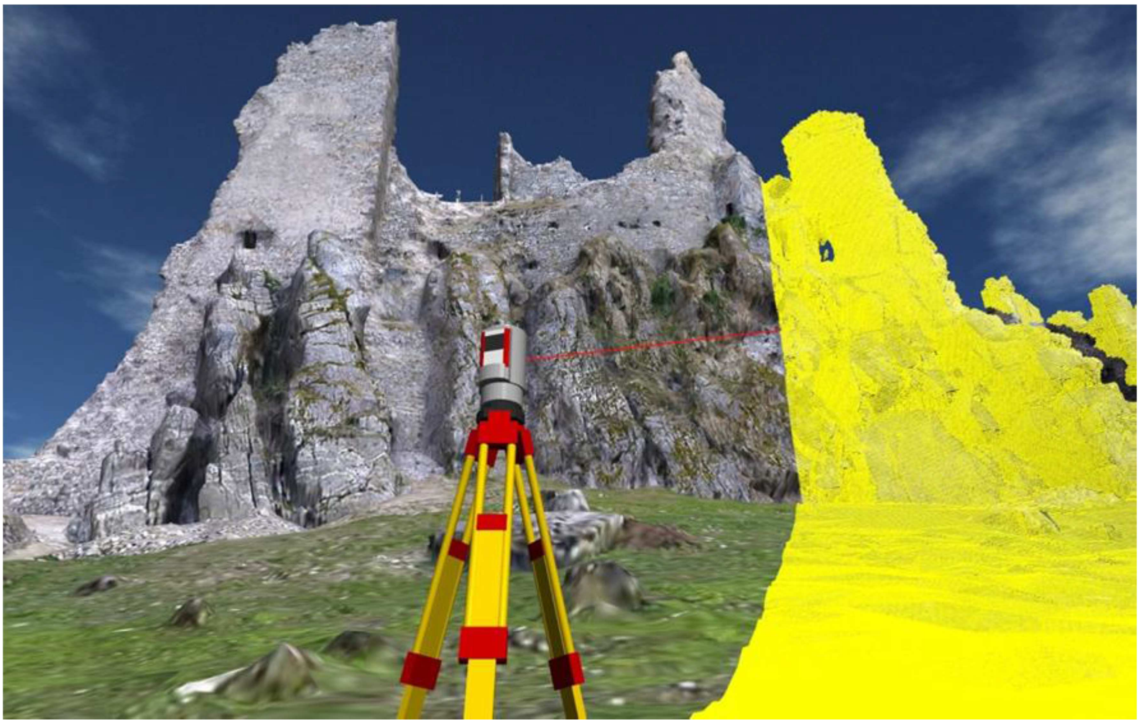


Figure 1: HELIOS simulating a terrestrial scan of a rock outcrop and castle ruin with a Riegl VZ-400 device. The red line indicates the path of the currently simulated laser beam, the yellow colour indicates the simulated point cloud. (Outcrop & Castle model: CC-BY-NC sketchfab.com)

In exemplary use cases, we run algorithms for 3D geologic outcrop characterization (ANDERS *et al.* 2016) and vegetation investigation (HÖFLE *et al.* 2015) on point clouds artificially generated with HELIOS. Virtual outcrop models are captured from different scan positions with different scan settings (e.g. beam divergence), leading to changes in point density and occlusion effects. Furthermore, occlusion effects of vegetation in outcrop scans are examined. We show that with our HELIOS framework, valuable test and benchmark data can be provided for method development. We conclude that the tool can support scanning campaign planning and field work, thus being of high value for the geoscientific community.

References

ANDERS, K., HÄMMERLE, M., MIERNIK, G., DREWS, T., ESCALONA, A., TOWNSEND, C. & HÖFLE, B., 2016. 3D geological outcrop characterization: automatic detection of 3D planes (azimuth and dip) using lidar point clouds. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., III-5, 105-112.

BECHTOLD, S. & HÖFLE, B., 2016. HELIOS: A multi-purpose Lidar simulation framework for research, planning and training of laser scanning operations with airborne, ground-based mobile and stationary platforms. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, III-3, 161-168.

HÖFLE, B., KOENIG, K., GRIESBAUM, L., KIEFER, A., HÄMMERLE, M., EITEL, J. & KOMA, Z., 2015. Lidar vegetation investigation and signature analysis system (LVISA). *Geophysical Research Abstracts*, 17(EGU2015-1537-1): 1-1.

PICKEL, A., FRECHETTE, J.D., COMUNIAN, A. & WEISSMANN, G.S., 2015. Building a better training image with digital outcrop models. *Journal of Hydrology*, 531(I): 53–61.

Geological Registration and Interpretation Toolbox (GRIT): A visual and interactive approach for geological interpretation in the field

Christian Kehl[1,2,*], James R. Mullins[3], Simon J. Buckley[1,2], Rob L. Gawthorpe[2], John A. Howell[3], Ivan Viola[4] & Sophie Viseur[5]

[1] *Uni Research AS, Nygårdsgaten 112, 5008 Bergen, Norway; christian.kehl@uni.no*
[2] *Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway*
[3] *University of Aberdeen, Dept. of Petroleum Geology, AB24 3UE Aberdeen, UK*
[4] *Inst. of Computer Graphics and Algorithms, Technical University of Vienna, 1040 Vienna, Austria*
[5] *Aix Marseille Université, CNRS, IRD, CEREGE UM 34, Sedimentary Systems and Reservoir Department, Marseille, France*

Key words: *virtual outcrop geology, outcrop analogues, field interpretation, visual computing, mobile devices.*

Digital interpretation software is increasingly used in geology to study photorealistic surface models of outcrops generated using lidar or photogrammetry/structure from motion (SfM). The results of 3D modelling can be used for presentation, manipulation and interpretation of acquired surface models to support the understanding of geological concepts and analogues. Interpretations (e.g. stratigraphic logs, demarcation of structural and sedimentological features) can be imported in as application-specific software, e.g. for hydrocarbon reservoir modelling (BUCKLEY, *et al.*, 2010). Workflows have been developed to provide sedimentary and structural data by combining field observations into virtual outcrop analogues (RITTERSBACHER, *et al.*, 2013).

A recent trend has been to adapt workflows further towards field integration, as envisaged by McCaffrey *et al.* (MCCAFFREY, *et al.* 2005), using laptop-executable software for modelling purposes (e.g. SIGMA (JORDAN, 2009)) and mobile devices for digital data acquisition (e.g. MAP-IT (DE DONATIS & BRUCIATELLI, 2006), FieldMove by Midland Valley Ltd.; SedMob (WOLNIEWICZ, 2014)). Here, the goal is to maximize efficiency in the field, capture relevant geological measurements, and reduce or enhance post-fieldwork digitization. Although the use of mobile devices for conducting geological fieldwork is increasing, the exploited capabilities of handheld devices currently do not reach their full potential. Modern mobile devices (i.e. smartphones and tablets) are able to process data more rapidly, conduct more complicated analysis than simple measurement acquisition, and thus can be used for more complex tasks in the field. Their processors, in combination with integrated digital cameras, apply well to for direct 2D photo manipulation. In addition, motion, orientation and positioning sensors facilitate full 3D image registration, and their processing units allow photorealistic outcrop models to be displayed with interactive frame rates. The potential has been previously demonstrated by VISEUR *et al.* (2014), using the commercial off-the-shelf Unity3D engine. VISEUR *et al.* (2014) further introduces the motivation for the development of mobile device field tools.

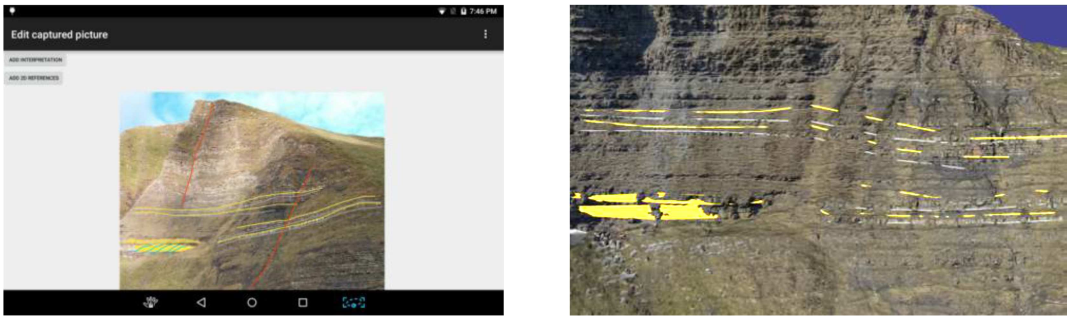


Figure 1: GRIT comprises a 2D interpretation mode (left) for polygon- and line interpretations of stratigraphic (yellow,grey) and structural (red) features and a 3D viewer (left) of the virtual outcrop and interpretations (right), running on mobile devices.

In this research, we explore the computing capabilities of mobile devices, and their contribution to geological fieldwork. In contrast to VISEUR *et al.* (2014), we use available 3D data directly during fieldwork and excursions. This is done within a new tool that closely links field observation in photos with an outcrop model. The application allows for fully geo-referenced photo captures and their geological interpretation on a sketching basis

(Fig. 1, left), using integrated Image-to-Geometry registration procedures (KEHL *et al.*, 2015). Furthermore, a virtual outcrop viewer provides rendering and navigation for 3D data (Fig. 1, right) analogous to previous approaches, but utilizing open source graphics software. All software components run entirely on the mobile device and independent of network connectivity, which can be an issue in remote locations.

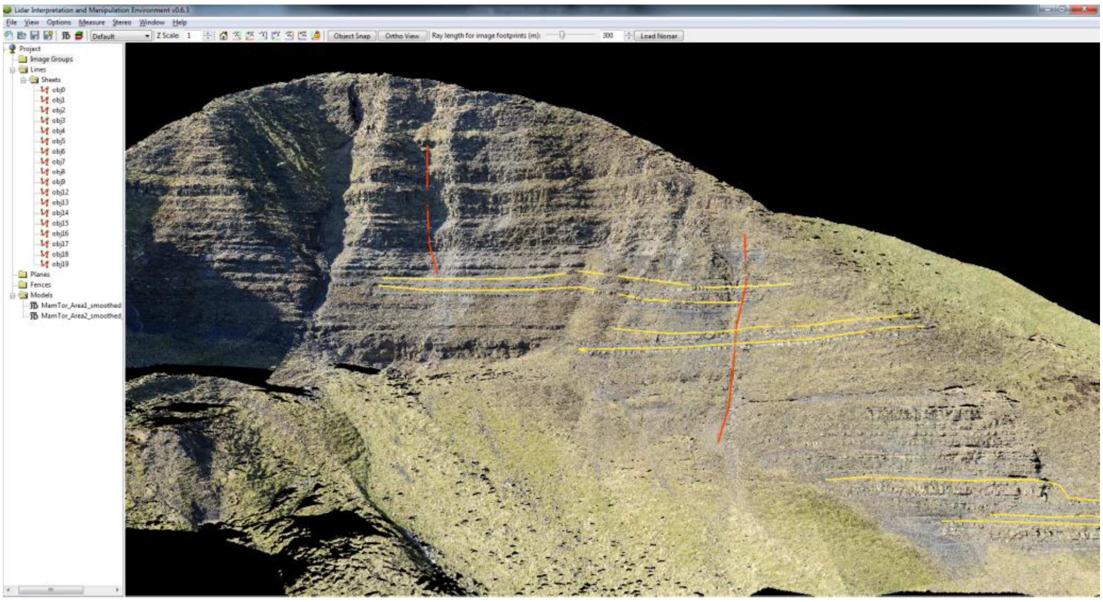


Figure 2: Imported 3D interpretation structures in desktop LIME software, based on projected mobile photo-interpretations.

Case studies assess the approach using outcrop localities in the UK. The field tests show the application of the software for deriving stratigraphic interpretations in a 3D-registered environment for the purpose of reservoir modelling. The derived interpretations are exported for quality control to LIME (Fig. 2), a desktop environment for virtual outcrop interpretation and data export to reservoir modelling packages. Experiences on device and user interface limitations are in line with VISEUR *et al.* (2014). These shortcomings and challenges are discussed further and taken as a basis for future research directions.

Acknowledgements: This research is part of the VOM2MPS project (no. 234111/E30), funded by the Research Council of Norway (RCN) and FORCE consortium through Petromaks 2 and SAFARI. Data are provided by the SAFARI project.

References

BUCKLEY, S. J., SCHWARZ, E., TERLAKY, V., HOWELL, J. A. & ARNOTT, R. W., 2010. Combining aerial photogrammetry and terrestrial lidar for reservoir analog modeling. *Photogrammetric Engineering & Remote Sensing*, 76(8): 953-963.

DE DONATIS, M. & BRUCIATELLI, L., 2006. MAP IT: The GIS software for field mapping with tablet PC. *Computers & Geosciences*, 32: 673-680.

JORDAN, C., 2009. SIGMAmobile: the BGS digital field mapping system in action: in the United Arab Emirates.

KEHL, C., BUCKLEY, S. J., & HOWELL, J. A., 2015. Image-to-geometry registration on mobile devices - an algorithmic assessment. *Proceedings of 3D NordOst, Berlin 2015*: 17-26.

MCCAFFREY, K., JONES, R., HOLDSWORTH, R., WILSON, R., CLEGG, P. & IMBER, J., 2005. Unlocking the spatial dimension: digital technologies and the future of geoscience fieldwork. *Journal of the Geological Society*, 162(6): 927-938.

RITTERSBACHER, A., BUCKLEY, S. J., HOWELL, J. A., HAMPSON, G. J. & VALLET, J., 2013. Helicopter-based laser scanning: a method for quantitative analysis of large-scale sedimentary architecture. *Geological Society, London, Special Publications*, 387(3): 185-202.

VISEUR, S., ROUDAUT, P., BERTOZZI, R., CASTELLI, M. & MARI, J.-L., 2014. 3D interactive geological interpretations on digital outcrops using a touch pad. *Proceedings of the 1st Vertical Geology Conference*, Lausanne, Switzerland.

WOLNIEWICZ, P., 2014. SedMob: A mobile application for creating sedimentary logs in the field. *Computers & Geosciences*, 66: 211-218.

Session 8

Chair: John Howell, University of Aberdeen

Terminus Hall

Friday 10:40 – 12:00, 23rd September

Fracture network characterisation using multi-scale UAV imagery, line extraction and stochastic simulation tools

Nico Hardebol[1,*], Beril Sirmacek[2], Kevin Bisdom[1], Gatien de Callatay[1,2], Roderik Lindenbergh[2] & Giovanni Bertotti[1]

[1] Delft University of Technology, Dept. of Geoscience and Engineering, Delft – NL;
[2] Delft University of Technology, Dept. of Geoscience and Remote Sensing, Delft – NL;
n.j.hardebol@tudelft.nl

Key words: *fracture network, extraction, parameterisation, photogrammetry, UAVs.*

Outcrops offer hand-on access to geological features, such as fractures, which can strongly affect the mechanical or hydraulic reservoir behaviour, yet may not be traceable in geophysical subsurface exploration. However, capturing relevant geological features in a quantitative and accurate manner is still a challenge.

Our capabilities to depict geologic structures in high resolution 3D has greatly improved with new acquisition techniques that involve photogrammetry based on photo collections acquired with lightweight unmanned aerial vehicles (UAVs; GILLESPIE *et al.*, 2011; SPENCE *et al.*, 2014). These new developments deliver birds-eye perspective and high resolution textured surface descriptions of geologically significant outcrop surfaces. Whereas the development of UAVs and photogrammetry tools is rapidly advancing, methods for extracting geological features are still limited (MASOUD & KOIKE, 2011), in particular for obtaining relevant fracture network properties.

More quantitative workflows need to be introduced that integrate qualitative field observations with the quantitative extraction of geological features that are critical for the characterisation of a subsurface structural fabric (MASOUD & KOIKE, 2011). Such a pursuit is particularly useful for studying fracture networks as these are often complex multi-scale systems that require high-resolution models of large areas.

We present a workflow that captures fracture networks as explicit line traces and as a parametrisation of the structural fabric. Three case studies are presented (Fig. 1) based on UAV-acquired imagery and photogrammetry: (1) fracture characterization of a coastal pavement of Jurassic shales in Yorkshire and (2) pavement of Cretaceous carbonates in the Potiguar Basin, NE Brazil, (3) a 3D textured surface of an anticlinal fractured dip slope in Tunisia. These cases exemplify our use of photogrammetry techniques not just for building complex 3D geological models but for characterizing the structural fabric. To this end we present the use of our in-house DigiFract software (HARDEBOL & BERTOTTI, 2013) and outline how we apply the Hough Transform based lineament extraction and fracture fabric parameterisation.

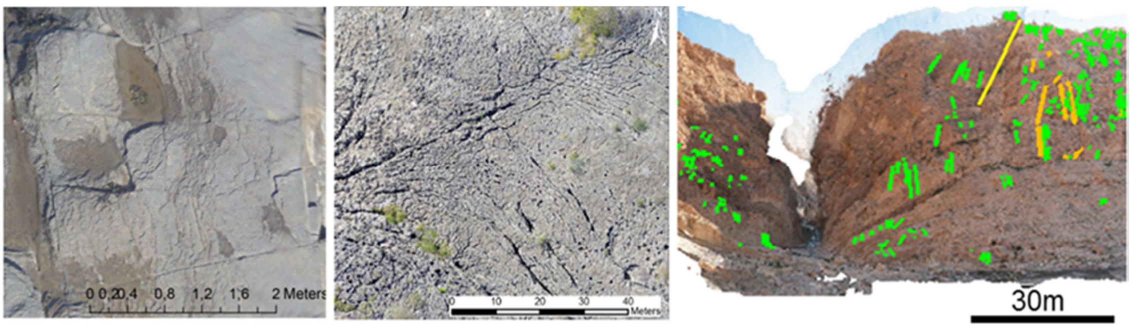


Figure 1: Imagery and textured surfaces of our case studies depicting fracture networks. (a) m-scale fracture network in Yorkshire shales (b) 100 m scale curvilinear fracture fabric in Brazil (c) 3D outcrop of fractured anticline flank, Tunisia.

Line detection procedures that are commonplace in wide range of remote sensing applications are examined, aiming for lineament extraction and parameterisation of the structural fabric (Fig. 2). The Hough Transform (HT; DUDA & HART, 1972) is the classical approach for finding parameterized shapes in images. The HT translates the problem of detecting spatially spread patterns to that of finding localized peaks in a dual parameter space. Applying the HT for detecting curvilinear fractures in our case studies, we found that the success of auto-tracked lineaments strongly depends, upon other input parameters, on pre-set cancellation range around and a minimum length of the auto-tracked trace.

In conclusion, using the translation of line patterns to distance-to-angle parameterisation (the HT method) serve the extraction of lineaments, and also help the characterization hand-drawn fracture traces. Such a parameter space characterisation is informative of the structural rock fabric as input in stochastic fracture network simulations. Our study shows how this both improves our fracture extraction capabilities from imagery as it invites us to explore in how far outcrop image holds information on upscale fabric properties such structural anisotropy with implications for fluid percolation.

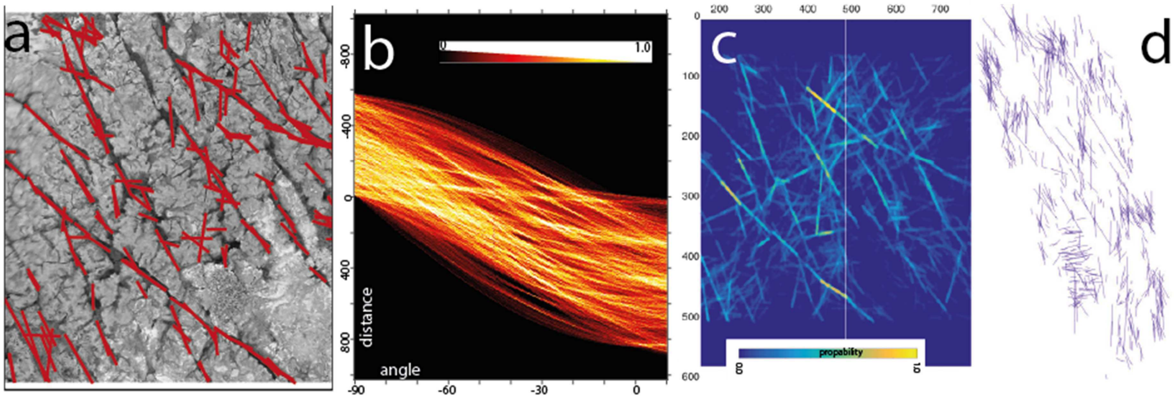


Figure 2: Fracture extraction and network parameterisation using Hough Transform. (a) the auto-traced fractures, (b) the distance-to-azimuth-angle parameter space diagram (c) Lineament probabilities from repeated tracking. (d) Stochastic fracture network model according to the distance-to-azimuth-angle parameterisation.

Acknowledgements: Our UAV hardware was supported by the Dutch research school ISES. We thank our industry sponsors for the financing of our outcrop analogue studies with the Yorkshire pavements studied under the Dutch Topsector Upstream Gas funded 2F2S research program, for the Tunisia field study with Total and Brazil pavement studies in a collaboration with UFRN (Natal) and Petrobras.

References

DUDA, R.O. & HART, P. E., 1972, Use of Hough transform to detect curves and lines in pictures. *Commun. ACM*, 15: 11-15.

GILLESPIE, P., MONSEN, E., MAERTEN, L., HUNT, D., THURMOND, J. & TUCK, D., 2011, Fractures in carbonates: from digital outcrops to mechanical models. In: Outcrops Revitalized: Tools, Techniques and Applications, *SEPM Concepts in Sedimentology and Paleontology*, 10: 137-147.

SPENCE, G.H., COUPLES, G.D., BEVAN, T.G., AGUILERA, R., COSGROVE, J.W., DANIEL, J.-M. & REDFERN, J., 2014. Advances in the study of naturally fractured hydrocarbon reservoirs: a broad integrated interdisciplinary applied topic. In: Advances in the Study of Fractured Reservoirs. *Geol. Soc., London, Spec. Pub*., 374: 1-22.

HARDEBOL, N. J. & BERTOTTI, G., 2013. DigiFract: A software and data model implementation for flexible acquisition and processing of fracture data from outcrops. *Computers & Geosciences*, 54: 326-336.

MASOUD, A. A. & KOIKE, K., 2011 Auto-detection and integration of tectonically significant lineaments from SRTM DEM and remotely-sensed geophysical data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66: 818-832.

3D modelling of fractures from DOM and field data: Characterization of spatial distribution patterns in fracture corridors

Sophie Viseur, Nadjet Bachtarzi, Sébastien Chatelée, Jules Fleury & Juliette Lamarche

Aix-Marseille Université, CEREGE, UMR 7330, 3 place Victor Hugo, 13331 Marseille, France

Key words: *fracture corridor, Digital Outcrop Models, fracture density, modelling.*

Fractures have major impacts on fluid flow in carbonate reservoirs (ANTONELLINI *et al.*, 1994; GAUTHIER *et al.*, 2000, HANSFORD *et al.*, 2009). Many geostatistical approaches have been proposed to model 3D fracture networks (BONNEAU *et al.*, 2013) within structural 3D reservoir models. These methods generally require information about fracture geometry, size, orientation and density. Moreover, different fracture characteristics have been defined in the literature (GAUTHIER *et al.*, 2012) depending on the dimension of the measured features (number, length, area, volume) and sampling zones (1D scanlines, 2D areas, 3D volumes). Fracture corridors are particular geological structures within which the fracture density is particularly high. Few studies have been devoted to characterize the geometry and spatial repartitions of fractures in fracture corridors. In this study, 3D Digital Outcrop Models (DOM) were acquired from a quarry at Calvisson and an outcrop at La Fare Les Oliviers (SE France). These numerical data were used as a support for interpreting and modelling fracture networks in order to study the fracture patterns in fracture corridors. Semi-automated techniques were used to extract fracture planes observed on outcrops. These surface patches constrained the 3D modelling of the fracture network. The obtained 3D model was finally compared with scanline information to understand the gap between 1D and 3D.

The Quarry of Calvisson is located on a formation composed of limestone. It includes a Hauterivian peloidal limestone corresponding to a packstone-wackestone, mostly homogeneous over the whole quarry. The quarry is divided into three floors on which fracture corridors are observed. A lidar acquisition was performed on the quarry to obtain a 3D representation of the quarry outcrops. Simultaneously, different field data were acquired: dips and scanlines. These outcrops stemming from a quarry are particularly interesting as fracture planes belongs to outcrop surface and are few altered. A comparable dataset was obtained using photogrammetry on an outcrop located at La Fare Les Oliviers (SE France).

As fracture planes belong to outcrop geometry, the objective is to help their interpretation by using geometrical attributes. In (GARCIA-SELLES *et al.*, 2011), a method is proposed to divide lidar data points into several set of fracture or stratigraphic planes. In (LE MEN *et al.*, 2014), several geometrical attributes were proposed to highlight and extract parts of fracture planes from the triangulated mesh of a DOM. An interesting point of this approach is to extract planes that are parallel to measured dip data of a fracture family. Thus, this last approach was used and enhanced to extract fracture geometries from the numerical outcrops and the field measurements.

Let (θ,α) be the measured dip azimuth and dip of a fracture family. The normal $\boldsymbol{N_f}$ of the measured fracture planes of this family is then defined as: $\boldsymbol{N_f} = (sin\alpha.cos\theta,\ sin\alpha.sin\theta, cos\alpha)^t$

Let $\boldsymbol{N_i}$ be the normal vector of a local ith triangle of mesh. Then, the two planes are parallel if their normal vectors are collinear, hence: $\boldsymbol{N_f}.\boldsymbol{N_i} = \pm 1\ \ or\ \ S_f = abs(\boldsymbol{N_f}.\boldsymbol{N_i}) = 1$.

Then, considering a threshold $t \in [0,1]$, it can be written that the triangle T_i belong to a fracture plane to detect if (Fig. 1): $S_f \geq t$.

Pre-processing on normal vectors may be applied to reduce noise due to mesh quality or data points. Manual validations and interpretations complete this procedure to assert to obtain reliable fracture geometries.

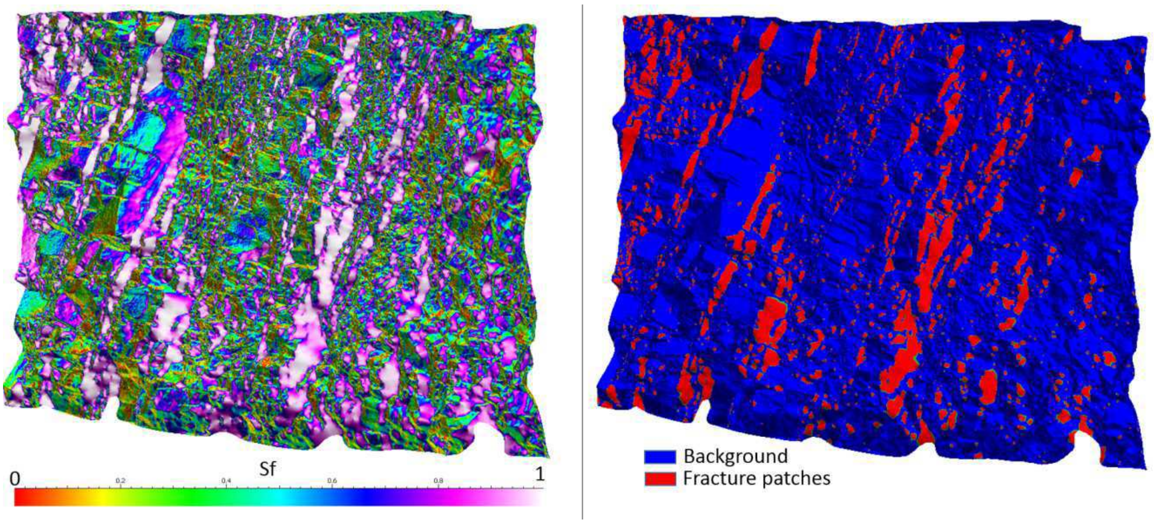


Figure 1: DOM geometrical attributes: left) Visualisation of S_f that corresponds to the absolute value of the scalar product between the local normal of a triangle and a normal of fracture planes measured in the field; right) binarization of the mesh using a threshold equal to 0.92.

3D models of fracture networks of the studied area are obtained. These models allow better understanding of fracture corridor patterns and spatial variability. The 3D fracture networks allow P30 values to be obtained and compared to fracture density obtained along scanlines (VISEUR *et al.*, 2016).

Acknowledgements: The authors would like to thank ParadigmGeo and ASGA for providing Gocad-Skua and the associated commercial and research-plugins. They also would like to thank Total SA for sponsoring this work.

References

ANTONELLINI M. & AYDIN, A., 1994, Effect of faulting on fluid ow in porous sandstones: petrophysical properties. *AAPG Bulletin*, 78: 355-377.

BONNEAU F., HENRION, V., CAUMON, G., RENARD, P. & SAUSSE, J., 2013. A methodology for pseudo-genetic stochastic modelling of discrete fracture networks. *Computers & Geosciences*, 56: 12-22.

GARCÍA-SELLÉS D., FALIVENE, O., ARBUÉS, P., GRATACOS, O., TAVANI, S. & MUÑOZ, J.A., 2011. Supervised identification and reconstruction of near-planar geological surfaces from terrestrial laser scanning. *Computer & Geosciences*, 37: 1584-1594.

GAUTHIER B., FRANSSEN, R. & DREI, S., 2000. Fracture networks in Rotliegend gas reservoirs of the Dutch offshore: implications for reservoir behaviour. *Netherlands Journal of Geosciences*, 79(1): 45-57.

HANSFORD J. & FISHE, Q., 2009. The influence of fracture closure from petroleum production from naturally fractured reservoirs: A simulation modelling approach. In: *AAPG Conference and Exhibition*.

VISEUR S., CHATELÉE, S., AKRICHE, C. & LAMARCHE, J., 2016. Approach for computing 1D fracture density: application to fracture corridor characterization. *Proceedings of EGU General Assembly, Vienna*.

Advances in the automated geometric extraction and analysis of geological bodies from virtual outcrops

Björn Nyberg[1*], Christian Haug Eide[1] Simon J. Buckley[2,1] & John A. Howell[3]

[1]*Department of Earth Sciences, University of Bergen, P.O. Box 7803, 5020 Bergen, Norway; bjorn.nyberg@uib.no*

[2]*Uni Research CIPR, P.O. Box 7810, 5020 Bergen Norway*

[3]*Department of Geology and Petroleum Geology, University of Aberdeen, Meston Building, AB24 3UE Old Aberdeen, UK*

Key words: *lidar, petroleum geology, shape analysis, geometry, stochastic modelling.*

Virtual outcrop geology (VOG) has seen significant developments over the past decade, with advances made to acquisition techniques such as terrestrial and helicopter-based lidar, photogrammetry and unmanned aerial vehicles, to improved software and processing workflows. This has facilitated geoscientists' ability to acquire and analyse increasingly large geological datasets, leading to more realistic, accurate and quantitative interpretations within a wide range of applications. In particular, largescale virtual outcrops have been used as analogues to subsurface aquifers, hydrocarbon reservoirs and CO_2 sequestration research to supplement traditional borehole and descriptive field-based observations. VOG is beneficial in correlating and recognizing the larger scale packages of sandbody and fault geometries that can have significant influence on subsurface fluid flow behaviour. By correlating large scale geometries with field-based observations, borehole and seismic data, quantitative datasets of qualitative geological information can be gathered with relative ease. However, as the practicality of gathering quantitative VOG data has improved, an increasingly prevalent problem is the relatively manual and subjective methodology for extracting quantitative geometric information and shape of interpreted sandbodies.

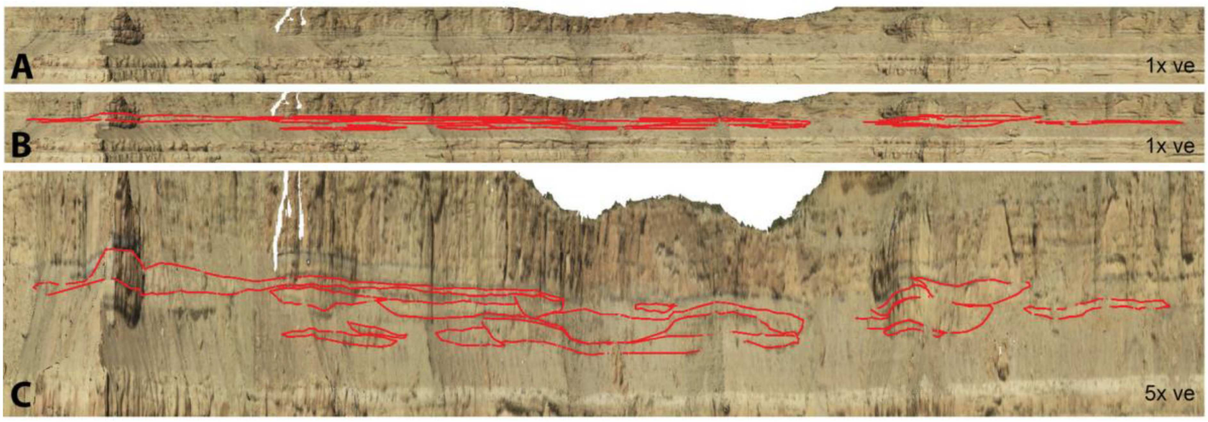


Figure 1: (A) shows a virtual outcrop of a ~1.7 km long by ~50 m thick succession of channel deposits in the Cretaceous Blackhawk Formation of eastern Utah. (B) shows the manually-interpreted channel belts with no vertical exaggeration. (C) shows the same interpretation with 5x vertical exaggeration for clarity.

To quantitatively analyse architectural elements in a photorealistic model, interpretations of e.g. sandbodies are typically digitised and geometric measurements manually made in an interactive 3D environment, Fig. 1. The shape and geometries of those sandbody measurements can provide important geometric constrains on geological sandbodies, which are then simulated in the subsurface using stochastic models. The geometry, shape and relationships between different sandbodies and associated heterogeneities have important implications on subsurface flow behaviour. While there have been previous efforts for automated fracture mapping and 3D training image extraction, a method lacks for the automated description of geometric data and shape from virtual outcrop geobodies.

In this contribution, we propose a method for the automated description of shape and geometry of interpreted geological features on a VOG model. By automatically defining the centreline of each individually interpreted sandbody, measurements of both width and centreline deviation are used to define a series of parameters for interpreting the shape and geometry of sandbodies. The automatic method makes it possible to analyse datasets that would be impractical by manual alternatives. The multiple measurements of width and centreline deviation for each individually interpreted sandbody can furthermore be used to describe and reproduce those shapes in stochastic-based modelling thereby providing a valuable tool to apply outcrop interpretations directly as analogs for a particular subsurface application. As the relatively new discipline of VOG continues to grow, innovative methods to analyse the increasingly quantitative datasets need to be addressed, offering new opportunities to efficiently study even larger geoscientific questions.

Acknowledgements: The FORCE consortium of oil companies is thanked for their support and funding for this work as part of the SAFARI phase II project.

Fault extraction using multi-remote sensing images

Li Wei[1*], Shichao Xu[1] & Xiaohu Zhou[2]

[1] *Department of Geology, Northwest University, P.O. Box 710069, Xi'an, China; weili2941@163.com*
[2] *State Key Laboratory of continental Dynamics, Northwest University, Xi'an, China*

Key words: *Danfeng area, fault structure, remote sensing image, information extraction, field verification.*

Many multi-stage faults of different scales and characteristics were developed in the Qinling orogenic belt, where the regional trunk faults are well studied. However, the research of associated secondary faults had relatively become the weak point and their properties, occurrence and relations with regional trunk faults not yet clear. Danfeng, Qinling was selected as the study area because of its landforms of mainly mountains and plains and well-developed faults, which was challenging for the implementation and validation of remote sensing extraction methods. In addition, the high rate of vegetation coverage, another notable feature of the study area, could offer a positive reference for the fault extraction in similar conditions. It is easy to recognize that the characteristics of rich spectral information, high spatial resolution and wide field view of remote sensing data could make the faults, which were presented in a form of linear information on remote sensing images. Compared to the conventional field work investigation, remote sensing extraction methods could not be limited by climate, topography and other factors. Meanwhile, these methods could be taken as the supplementary research techniques owning to the macroscopic characteristic of remote sensing images.

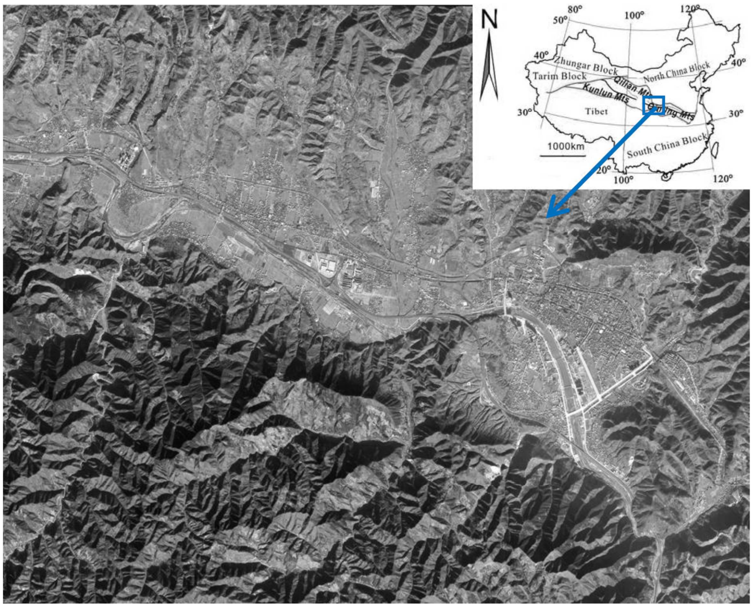


Figure 1: The remote sensing map of Qinling Mountains Danfeng area.

Combined with the field investigation, the distribution and characteristics of the faults were revealed through the extraction methods of multi-source remote sensing images, such as IRS-P6, ETM+, OLI, Google Earth data and SRTM. The following methods were adopted for the interpretation and extraction of the faults. Firstly, colour synthesis, principal component analysis, directional filtering, image fusion and ratio calculation, combined with three-dimensional display, were used to enhance the spatial structure information and spectral information of faults and establish the interpretation signs of study area. Meanwhile, interpretation results were tested on field areas. Secondly, automatic extraction using median filter-edge detection-Hough transform was directly utilized to detect the faults in the study area.

The results of these methods were encouraging. Major faults in study area were well-extracted through the method of automatic extraction. Moreover, the properties of these faults were judged on the basis of interpretation signs of synchronous bending of river systems, ridge twists, etc.

The distribution characteristics and properties of major faults, such as Meijiawuchang-Chenjiawuchang Fault (F2), Wafangcun-Anjiping Fault (F3), Huiyu-Damiaogou Fault (F4), and Yueritan-Wangjiagou Fault (F5), were significantly affected by regional main faults of ShangDan (F1) and primarily controlled by NNW sinistral strike-slip faults. Not only were the recorded faults extracted, but also a number of new faults were interpreted and tested, which could greatly enrich the geological structure information of this area. The faults were mainly close to NNW trending, EW in some individual area, and basically presented the nature of sinistral strike-slip.

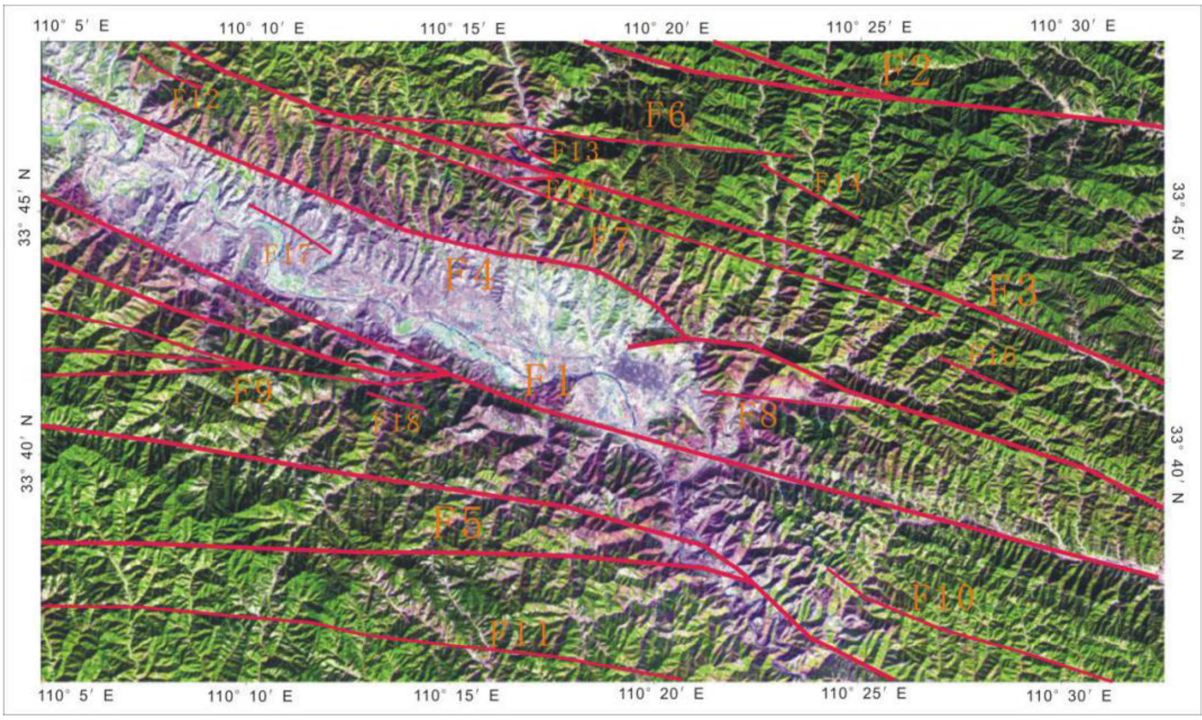


Figure 2: the final results for the study area. F1.Shangdan Fault Zone; F2.Meijiawuchang-Chenjiawuchang Fault; F3.Wafangcun-Anjiping Fault; F4.Huiyu-Damiaogou Fault; F5.Yueritan-Wangjiagou Fault; F6.Laoyemiao-Sixinggou Fault; F7.Longwangmiaocun-Dazhuangcun Fault; F8.Xigou-Madi Fault; F9.Sanchazi-Baodingcun Fault; F10.Youfang-Chagou Fault; F11.Wafang-Malucun Fault; F12.Xiayaozhuang Fault; F13.Yuling Reservoir Fault; F14.Wangjiacun Fault; F15.Yulingcun Fault; F16.Xiaogou Fault; F17.Gongjiahecun Fault; F18.Balishi Fault.

Session 9

Chair: Daniel Wujanz, TU Berlin

Terminus Forum

Friday 10:40 – 12:00, 23rd September

Surface roughness analysis of fossil oyster shells using 3D laser scanning data

Ana Djuricic[1,2*], Mathias Harzhauser[2], Oleg Mandic[2] & Norbert Pfeifer[1]

[1] *Department of Geodesy and Geoinformation, Vienna University of Technology, Gusshausstrasse 27-29, 1040, Vienna, Austria; ana.djuricic@geo.tuwien.ac.at; norbert.pfeifer@geo.tuwien.ac.at*
[2] *Geological Paleontological Department, Natural History Museum Vienna, Burgring 7, 1010 Vienna, Austria; mathias.harzhauser@nhm-wien.ac.at; oleg.mandic@nhm-wien.ac.at*

Key words: *3D laser scanning, 1mm DSM, surface roughness, fossils, oyster shell.*

Laser scanning technology provides a precise and objective methodology for documenting paleontological objects from in-situ localities (to support for instance museum digital documentation). It is a non-destructive approach for documenting in-situ fossils, capturing the geological context and expanding the availability of specimens that may be rare or fragile. This technique was recently applied for a 3D modelling of a protected fossil oyster reef exposed in the geopark "Fossilienwelt Weinviertel" in NE Austria (HARZHAUSER *et al.*, 2015, 2016). The site represents the world's largest fossil oyster reef, but due to the fragility of the fossils it is difficult to study.

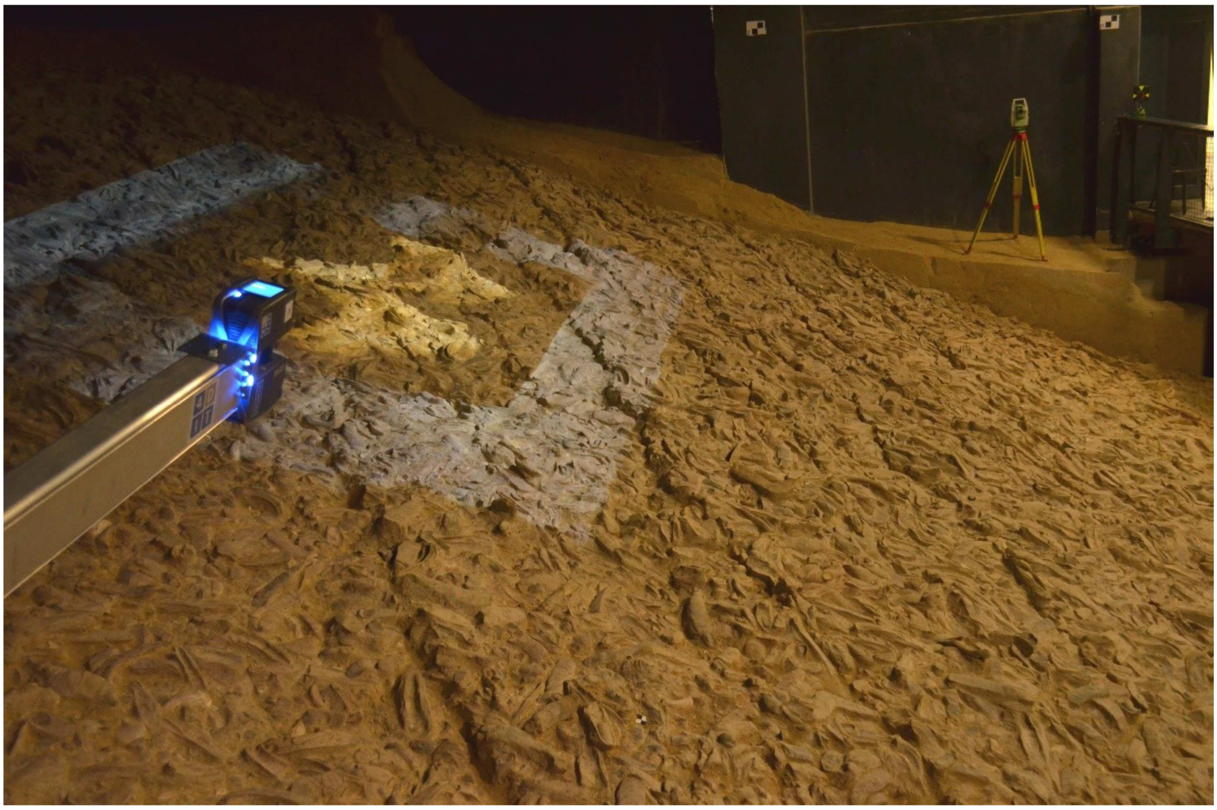


Figure 1: Terrestrial laser scanning campaign on the world's largest fossil oyster reef in the exhibition hall at Stetten in Austria.

The reef's digital surface model provides extensive digital data for developing new algorithm workflows for roughness quantification on individual oyster shell. This allows reliable computations of surface shell condition, i.e. surface roughness used in paleontological analyses of bioerosion, epibenthic overgrowth or abrasion (smoothness of shells). Roughness is derived automatically from geometry data based on the vertical component of surface normals, the sigma0 (standard deviation of plane fitting residuals of reef points) and the local slope (steepness indicator).

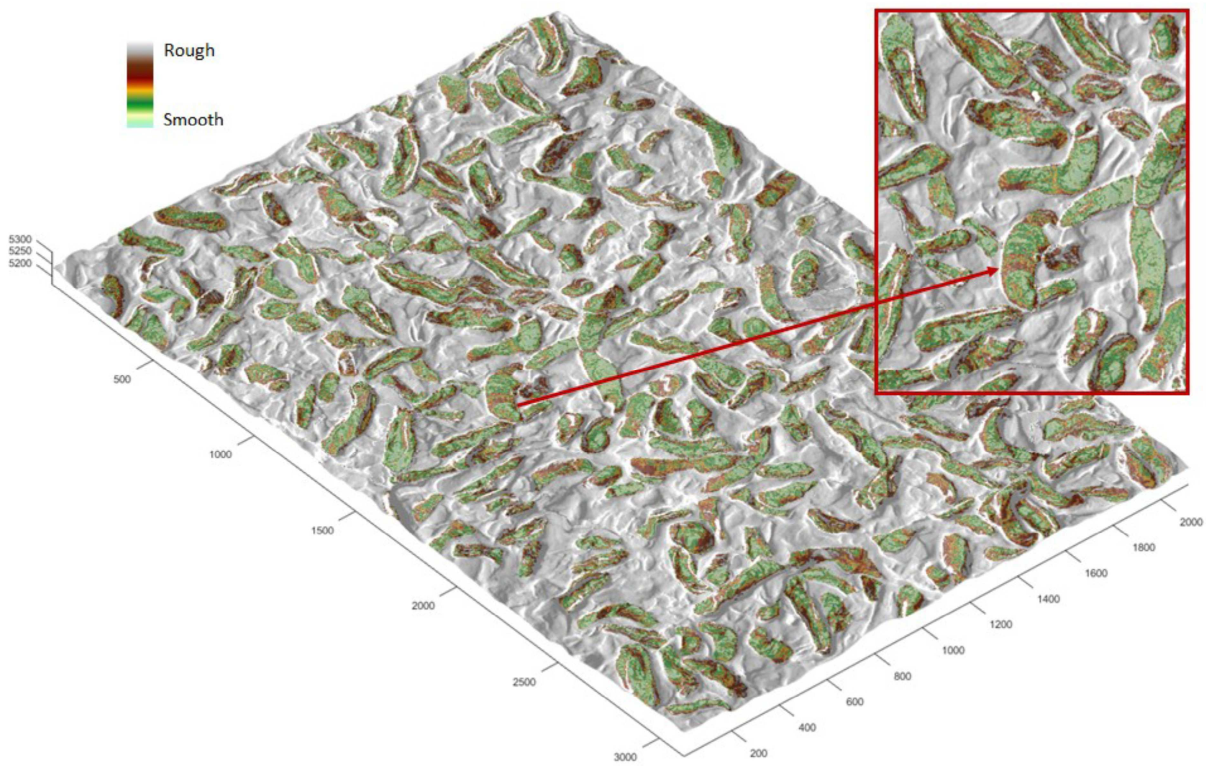


Figure 2: Surface model overlapped with the roughness layer of identified individual fossil shells of an area of 3m x 2m; (right) detail of complete convex up oyster valve and its surrounding.

We are examining how the surface roughness on individual oyster shells is affected when using varying neighbourhood window sizes. Oyster shells are identified from a 1mm digital surface model derived from the laser scanning point cloud. This method was tested on a set of reference data (over 400 shells covering an area of 6 m^2), justified through palaeontology experts by cross-checking with high resolution orthophotos (0.5 mm).

The visualization and detection of shell surfaces within the complex surrounding on the oyster reef provides a new room to test and study possibilities of geometry features. Analysis of high resolution laser scanning data offers distinction between geometrical features and therefore supports the interpretation of surrounding topography, while it highlights both the highest and lowest parts of features. This makes 3D laser scanning an ideal candidate for interpretative mapping of paleontological sites. Moreover, laser scanning is also contributing in multidisciplinary investigations, combining its advantages with other disciplines such as photogrammetry, GIS, cartography, etc.

Acknowledgements: The project is supported by the Austrian Science Fund (FWF P 25883-N29). The authors would like to thank Peter Dorninger and Clemens Nothegger from 4D-IT GmbH, Austria for organizing the field campaign.

References

HARZHAUSER, M., DJURICIC, A., MANDIC, O., ZUSCHIN, M., DORNINGER, P., NOTHEGGER, C., SZÉKELY, B., PUTTONEN, E., MOLNÁR, G. & PFEIFER, N., 2015. Disentangling the history of complex multi-phased shell beds based on the analysis of 3D point cloud data. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 437: 165–180.

HARZHAUSER, M., DJURICIC, A., MANDIC, O., NEUBAUER, T. A., ZUSCHIN, M. & PFEIFER, N., 2016. Age structure, carbonate production and shell loss rate in an Early Miocene reef of the giant oyster Crassostrea gryphoides. *Biogeosciences,* 13: 1223-1235.

Determination of roughness parameters based on dense image matching and structured light scanning

Kristofer Marsch[1*] & Daniel Wujanz[2]

[1] Technische Universität Berlin, Institute of Applied Geosciences, Engineering Geology, Berlin, Germany; kristofer.marsch@tu-berlin.de

[2] Technische Universität Berlin, Institute of Geodesy and Geoinformation Science, Working Group for Geodesy and Adjustment Theory, Berlin, Germany

Key words: *data quality, dense image matching, structured light scanner, surface roughness.*

In order to describe the mechanical behaviour of a rock mass the shear strength of the discontinuities plays a vital role. The surface roughness is a major parameter that characterises the geometric component of shear resistance. In order to quantify roughness, index values for surfaces or profiles are computed preferably from accurate 3D models. A major problem in this context is that devices for precise 3D data acquisition, such as structured light scanners, are very costly and cumbersome to transport. It is obvious that such devices are impractical, especially in steep outcrops or mountainous regions. An interesting alternative is given through digital imagery which has been captured by consumer grade cameras. Current developments in photogrammetry and computer vision pursue the generation of 3D point clouds based on uncalibrated images. In this study, two ways of acquiring 3D models were compared, namely dense image matching and structured light scanning (SLS).

A major problem in this context is the determination of a scaling factor that transforms the generated 3D model into a metric representation. As this step systematically influences the quality of the outcome it can be rated as the most vital step in the processing chain of the whole procedure. In order to tackle this issue a lightweight, low-cost, precise and portable frame is presented that allows scale information in three cardinal directions to be reliably computed. The frame consists of carbon fibre tubes that are insensitive to thermal differences due to their low coefficient of expansion. In addition eight spherical markers are attached to the tubes whose 3D coordinates are known at high precision.

In this preliminary study a selection of various surfaces from different lithologies were mapped and parameterised under laboratory conditions. Data acquisition has been carried out with an uncalibrated camera (Nikon D800) as well as a GOM ATOS I structured light scanner that served as a reference. In a first step the data quality was evaluated. In this regard, it was seen that the 3D model acquired with dense image matching showed acceptable deviations to the reference. Finally various index numbers for the description of roughness were computed, namely JRC, Z2, θ*/[C+1] and RS (Barton & Choubey, 1977; Myers, 1962; Tatone & Grasselli, 2010; Belem *et al.*, 2000).

References

Barton, N. & Choubey, V., 1977. The shear strength of rock joints in theory and practice. *Rock Mechanics*, 10(1-2): 1-54.

Belem, T., Homand-Etienne, F. & Souley, M., 2000. Quantitative Parameters for Rock Joint Surface Roughness. *Rock Mech. Rock Engng.*, 33(4): 217-242.

Myers, N.O., 1962. Characterization of surface roughness. *Wear*, 5(3): 182-189.

Tatone, B.S.A. & Grasselli, G., 2010. A new 2D discontinuity roughness parameter and its correlation with JRC. *Int. J. Rock Mech. Min. Sci.*, 47(8): 1391-1400.

Characterization of geological structures with technical improvements in acquisition and processing

David García-Sellés[1*], Oscar Gratacós[1], Josep Anton Muñoz[1] & Sergio Sarmiento[2]

[1] *GEOMODELS Research Institute. Faculty of Geology. University of Barcelona, 08028Spain*
dgarcia@ub.edu
[2] *REPSOL 2455 Technology Forest Blvd, The Woodlands, TX,USA, TX 77381*

Key words: *lidar, naturally fractured reservoir, virtual reality.*

The characterization of fracture systems comprises, on the one hand, the individual characterization of fractures by their orientation (strike and dip), type, length, height, roughness, aperture and in-filling, and on the other hand their relationship expressed as spacing between fractures, the coefficient of variation (GILLESPIE, 1999), abundance (DERSHOWITZ & HERDA, 1992) and fracture length and height distribution among the most used classical parameters. Fracture systems characterization is commonly performed using field fracture measurements along scanlines in layered rock units and often confined in discrete horizons defined by their mechanical properties (GROSS, 1993).

In the last decade, improvements in software and hardware have allowed terrestrial laser scanner and photogrammetry data to have become widely used, with the aim to complement existing fracture characterization. In this sense, our group have developed algorithms to measure different properties along virtual scanlines in modelled fracture systems (SANTANA, 2012). In order to obtain automatically the Fracture Stratigraphy (LAUBACH, 2009), this virtual scanline can be repeatedly applied in a several parallel-to-bedding virtual scanlines with spacing of a few centimetres. As a consequence, the rock mass can be characterized and divided accordingly its fracture stratigraphy behaviour. Virtual scanlines and window samples are used to measure the classical parameters to characterize geometrically the outcrop.

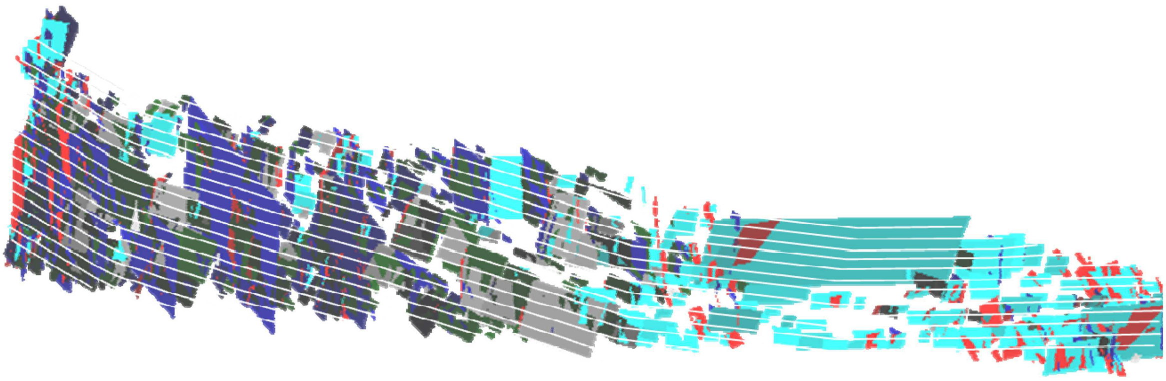


Figure 1: Image of virtual scanlines (white lines) methodology along a fracture model to obtain the Fracture Stratigraphy. The fracture model reconstructs the fracture sets by coloured planes.

This methodology is applied at Abra del Condor (Bolivia), a reservoir analogue outcrop placed at the Sub-Andean range, with an extension of 1.7 km of tight sandstones in 350 m sequence of Huamampampa formation.

Acknowledgements: This research is supported by Geomodels Research Institute, and financed by the projects CGL2014-54118-C2-1-R (SALTECRES), CGL2013-40828-R (CHARMA) from the Spanish Ministry of Science and Technology.

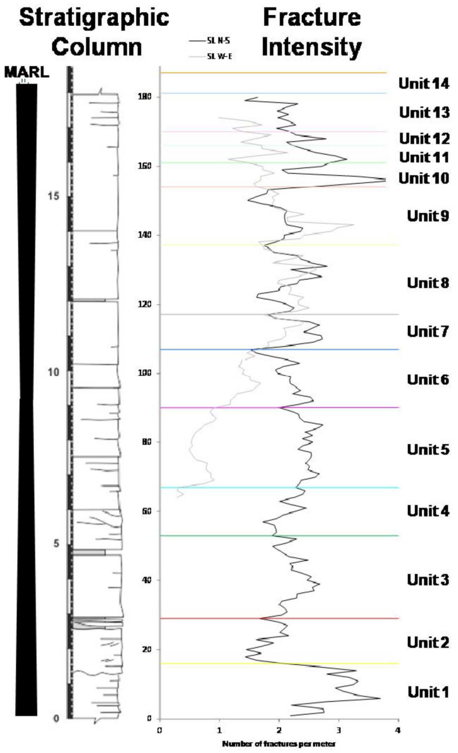


Figure 2: Example of correlation between fracture stratigraphy and stratigraphic column in a Pyrenean outcrop.

References

DERSHOWITZ, W. S. & HERDA H. H., 1992 Interpretation of fracture spacing and intensity. Tillerson, J. R. & Waversik, W. R. (eds.) Rock Mechanics. Balkema, Rotterdam, 757-766.

GILLESPIE, P.A., JOHNSTON, J.D., LORIGA, M.A.,MCCAFFREY, K.L.W.,WALSH, L. L. & WATTERSON, L., 1999. Influence of layering on vein systematics in line samples. In: McCaffrey, K.J.W., Lonergan, L., Wilkinson, J.J., Fractures, Fluid Flow and Mineralization. Geological Society, London. Special Publication, 155, pp. 35-56.

GROSS, M.R., 1993. The origin and spacing of cross joints: examples from the Monterey Formation, Santa Barbara coastline, California. *Journal of Structural Geology*, 15: 737-751.

LAUBACH, S.E., OLSON, J.E. & GROSS, M.E., 2009. Mechanical and fracture stratigraphy. *AAPG Bulletin*, 93, 11: 1413-1426.

SANTANA, D., COROMINAS, J., MAVROULI, O. & GARCÍA-SELLÉS, D., 2012. Magnitude-frequency relation for rockfall scars using a Terrestrial Laser Scanner. *Engineering Geology*, 145-146: 50–64.

Distinguishing facade material change using close-range hyperspectral imaging

Zohreh Zahiri[1*], Debra F. Laefer[1], Tobias H. Kurz[2] & Simon J. Buckley[2]

[1] University College Dublin, School of Civil Engineering, Dublin, Ireland; zohreh.zahiri@ucdconnect.ie
[2] Uni Research CIPR, P.O. Box 7810, N-5020 Bergen, Norway; tobias.kurz@uni.no

Key words: *building material, remote sensing, hyperspectral imaging, material detection.*

To conduct city-scale computational modelling for infrastructure planning, micro-climate analysis, and disaster mitigation, not only must the geometry of the built environment be detectable automatically but the component materials must be as well. While extensive work has been undertaken for geometric recognition and feature detection on buildings (e.g. VO *et al.*, 2015), relatively little has been done for material identification (ZHU & WOODCOCK, 2014). Furthermore, most of that work has been for the classification of urban land cover, with extremely limited analysis applied to building material identification.

Today, remote sensing data in the form of hyperspectral imagery are widely used for identification of materials in agriculture, environment, geology, astronomy, and more. Despite the widespread application of hyperspectral imaging in many areas, this method has seldom been used in building material detection. As aerial hyperspectral imagers do not get adequate information from building façades, close-range hyperspectral imaging, which is a newer technique applied from the ground and recently used to study geological outcrops (KURZ *et al.*, 2013), can be applied to evaluate building façade material.

This paper will investigate how different building materials can be differentiated using close-range remote sensing technology in the form of hyperspectral (near-infrared) data. For this purpose the façade of a building containing multiple materials in Bergen, Norway, was scanned by a close-range, hyperspectral instrument. After masking non-building material, several pre-processing techniques were applied on the hyperspectral images including atmospheric and brightness correction, morphology effect removal, and bad pixel correction. Different materials on the building were then classified using supervised classification techniques (Linear Spectral Un-mixing and Spectral Angle Mapper). The results showed the ability of hyperspectral data in the range of near infrared to differentiate distinctive building materials.

Figure 1: Hyperspectral image of building façade.

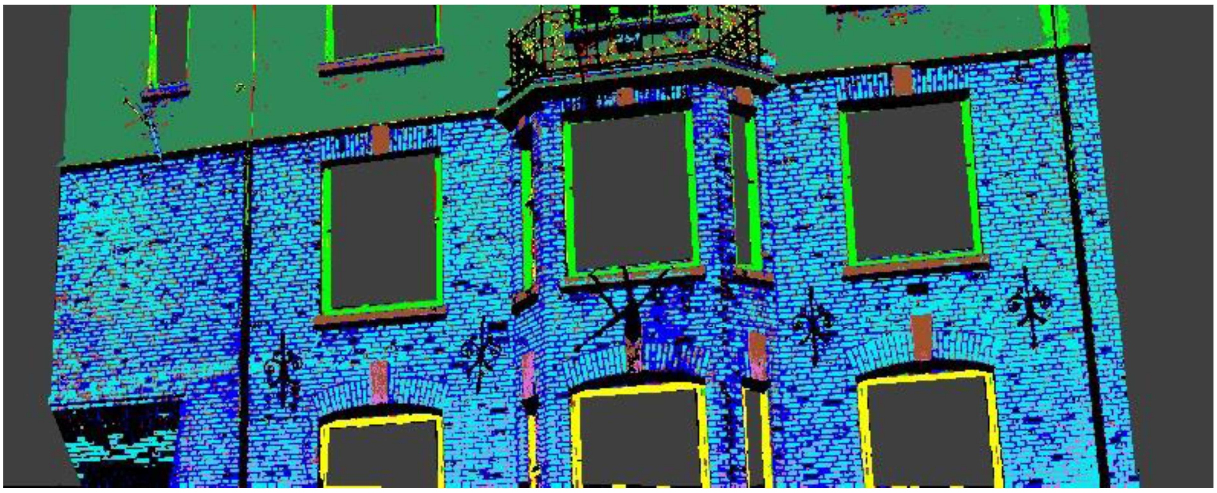


Figure 2: Classification image of building façade using Spectral Angle Mapper method.

References

KURZ, T. H., BUCKLEY, S.J. & HOWELL, J.A. 2013. Close-range hyperspectral imaging for geological field studies: workflow and methods. *International Journal of Remote Sensing*, 34: 1798–1822.

VO, A.-VU., TRUONG-HONG, L. LAEFER, D.F.& BERTOLOTTO, M., 2015. Octree-based region growing for point cloud segmentation. *ISPRS Journal of Photogrammetry and Remote Sensing*, 104: 88–100.

ZHU, Z, & WOODCOCK, C.E. 2014. Continuous change detection and classification of land cover using all available Landsat data. *Remote Sensing of Environment*, 144: 152–171.

Session 10

Chair: Sophie Viseur, Aix-Marseilles Université

Terminus Hall

Friday 13:00 – 14:20, 23rd September

Geostatistics and modelling algorithms for characterisation of sandstone intrusions

David Hodgetts[1*], Thomas Seers[1], Brian Burnham[1], Antonio Grippa[2], Giuseppe Palladino[2], Denis Bureau[1], Mads Huuse[1] & Andrew Hurst[2]

[1] SEES, The University of Manchester, Oxford Road, Manchester, M13 9PL. UK; david.hodgetts@manchester.ac.uk
[2] Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, AB24 3UF

Key words: *lidar, photogrammetry, sandstone intrusions, reservoir modelling, algorithms.*

Sand injection, the forceful remobilisation and injection of sand during burial, is now recognised as an important component of both new and existing reservoirs. These injection structures occur on scales from a few cm up to injection features visible on seismic data and 100s of metres in length.

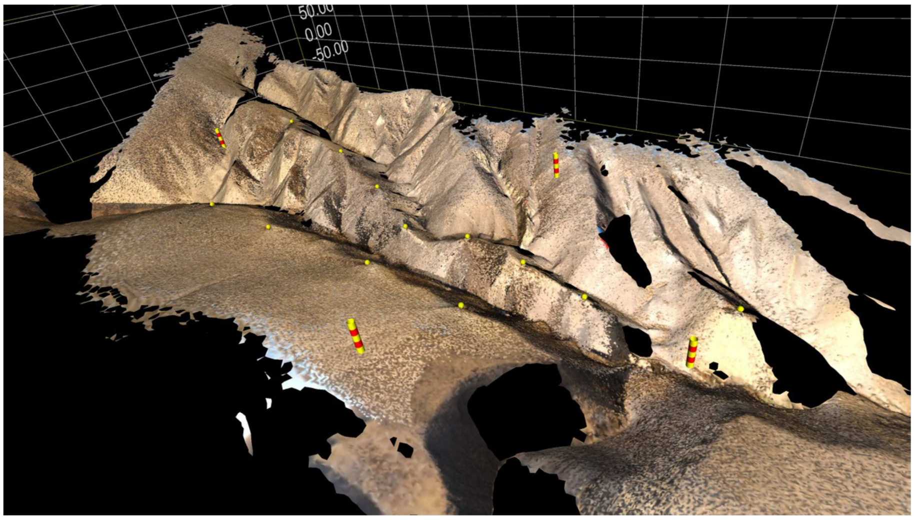


Figure 1: The Dosados Canyon Survey. The survey comprised scan positions collected using a Riegl LMS-Z420i laser scanner. Scale bars are 25m high.

The Panoche Giant Injection Complex (PGIC) exposed in the Panoche and Tumey Hills, San Joaquin Valley, California, provides intermittent exposure over an area of 100 km^2 (approx.), with exposures ideal for both lidar and structure from motion (SfM) studies. The PGIC formed during the Early Palaeocene and is intruded into mudstones of Late Cretaceous and Early Palaeocene age. Four lidar studies (see Fig. 1 for an example of one study area) and several SfM studies have been undertaken during the course of the project covering areas of best exposure and key scientific interest. These datasets have been used to map intrusion geometry and topology (Fig. 2) and extract geostatistical information on size, orientation and spacing and derive P22 maps (areal percentage) and in turn use these to estimate P33 volumes (volumetric percentage) for the studied areas.

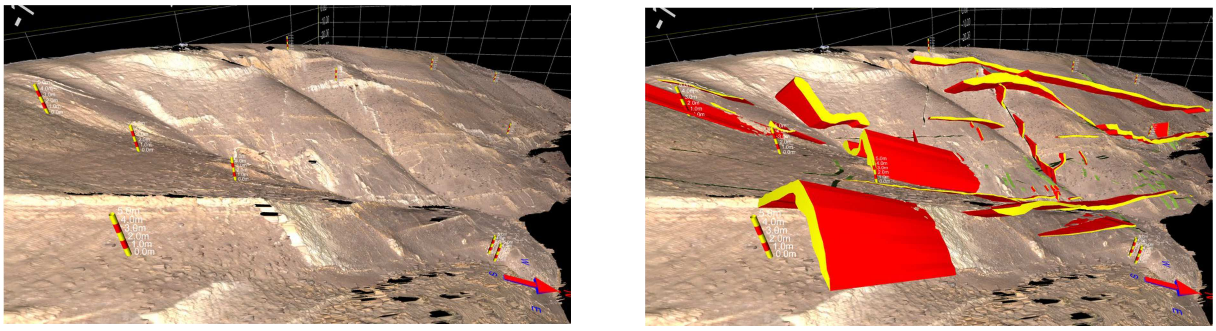


Figure 2: Photorealistic mesh derived from the lidar data (left) and geobodies and polylines interpreted on the digital model showing geometries and relationships between sandstone intrusions.

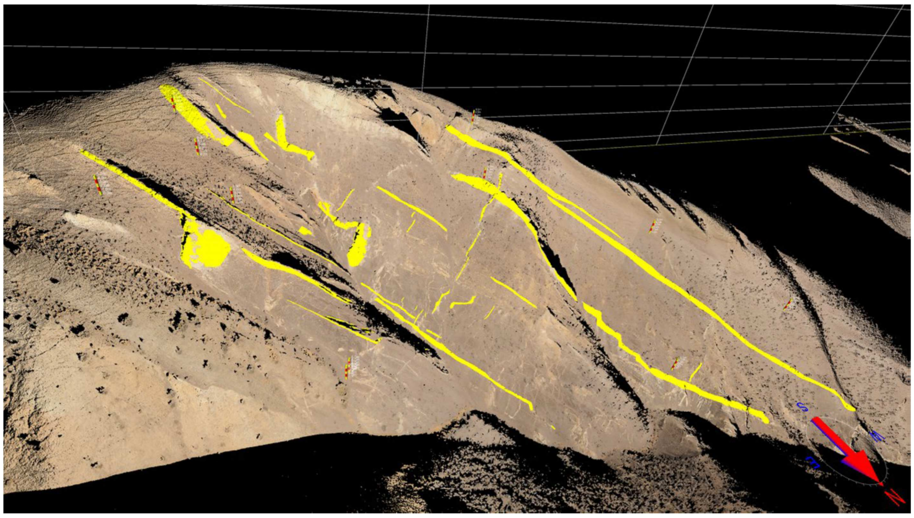


Figure 3: The point cloud classified for sandstone intrusions using the geobodies in Fig. 2. These data can then be upscaled into a modelling grid and then used as conditioning data for building geocelluar outcrop models.

The presence of sand injection features in a reservoir can, and do, impact reservoir performance by modifying reservoir connectivity away from that expect from the initial depositional architecture. The digital outcrop models provide geostatistics and conditioning data (Fig. 3) for building outcrop constrained geocellular models with facies classified point clouds providing an opportunity to extract variograms for the intrusion distribution. Current reservoir modelling systems, however, have difficulty in representing sand injection features for two primary reasons. 1) The injection features tend to be steep angle with respect to the initial stratigraphy with variability in both dip and azimuth, and reservoir modelling algorithms are not designed for this. 2) Many of the injection features which will modify the flow regime fall well below typical reservoir modelling resolutions. This 2nd problem cannot be addressed by simply increasing the model resolution as to achieve the resolution necessary the model would be too large to be usable. In order to successfully model these features, new approaches need to be developed in order to model their impact on petroleum reservoirs. As a result of this a new modelling algorithm has been developed to better improve the modelling of these complex systems in reservoir models (see Fig. 4). This algorithm uses a fractional Brownian motion (fBM) approach to build realistic sandstone intrusion geometries which may then be upscaled into a full reservoir model.

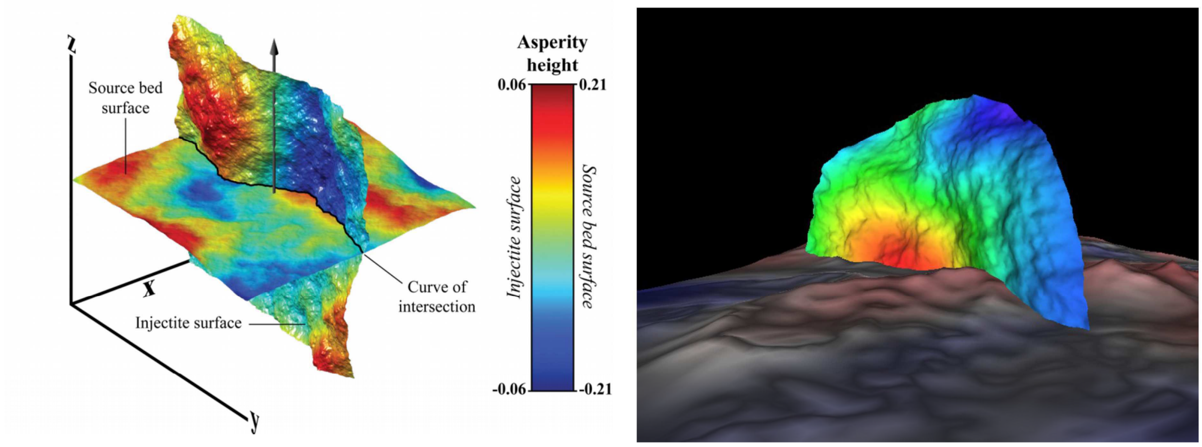


Figure 4: Sandstone Intrusions modelled as fractional Brownian motion (fBM) fractal surfaces.

Virtual outcrop mapping for CO_2 reservoir analogue modelling

Davide Pistellato[1*], Richard Murphy[2], Joan Esterle[1], Atefeh Sansoleimani[1] & Valeria Bianchi[1]

[1] *School of Earth Sciences, The University of Queensland, Brisbane, Australia; d.pistellato@uq.edu.au*
[2] *Australian Centre for Field Robotics, The University of Sydney, Sydney, Australia*

***Key words**: 3D modelling, photogrammetry, hyperspectral imaging, analogue modelling, mineral mapping.*

The Lower Jurassic Precipice Sandstone is an important reservoir for water, hydrocarbons and potentially CO_2 geosequestration in the Surat Basin. For geosequestration, knowing the occurrence of reactive minerals is important for modelling the interaction of the CO_2 with the host reservoir. It is the basal infill of the basin, and it is commonly interpreted as forming in a fluviatile system that accumulated a thick (up to ~200m) belt of sandstone located in correspondence to the structural axis of the basin, the Mimosa Syncline. The unit crops out along the northern margin of the basin, often forming laterally continuous cliffs that provide good conditions for 3D photogrammetry and classical 2D mapping and analysis of sedimentary architectures, bedding and facies (RARITY *et al.*, 2014). This was coupled with hyperspectral imaging to developing a 3D model of the outcrop and the mineral distribution.

3D terrestrial close range photogrammetry was performed along with a topographic RTK survey in order to extract 3D dense point clouds and generate solid models with extremely high photographic quality texture. These were used to measure surfaces, bed and body geometries for export to a reservoir modelling system, providing a bridge between the subsurface drilling data and the outcrop analogue.

To assist with the identification and lateral continuity of fine grained units and their mineralogical composition within the Precipice, quantitative mineral maps derived from hyperspectral imagery acquired from a field-based platform were integrated with photogrammetry (Fig. 1). Clay mineral-rich layers can impact on both reservoir permeability and the reactivity with CO_2. Iron and manganese oxides and hydroxides, phyllosilicates (clays) and carbonates can be detected by means of hyperspectral sensors (MURPHY *et al.*, 2014) measuring the visible near-infrared (VNIR) and short wave infrared (SWIR) spectral range. The integration of hyperspectral panoramic images with 3D photogrammetric data enabled different spectral signatures (indicative of changes in mineralogy) to be quantified, thus mapping the lateral continuity and thickness of layers on the exposed wall.

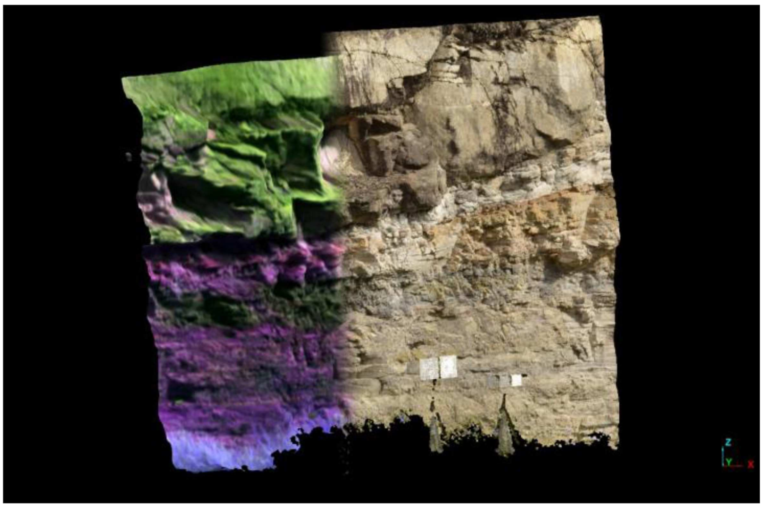


Figure 1: 3D photogrammetric model. Left: coloured by spectral images; right: photorealistic texture.

The attempt to transform image coordinates into object coordinates (KURZ *et al.*, 2011) may represent a real challenge when both the interior orientation and the calibration parameters are not known. However, the correspondence between the spectral panoramic imagery and the photogrammetric data was established by the identification of natural objects (GCP). Despite the limited spectral resolution, the proximity to the outcrop face and the minimal colour differences between the visible and the high quality texture images helped to achieve satisfactory registration accuracies with RMS errors of a few centimetres.

The preliminary field results particularly demonstrate that the gross clay mineralogical (e.g. kaolinite) and iron oxide changes follow the bulk changes in lithology (siltstone and sandstone), as do patterns of absorption by molecular water, but discrimination is poor where there are no sharp boundaries (Fig. 2). Although the spatial resolution and mineralogical identification might be improved, this technique shows great promise because it highlights the distribution of siltstones beds and drapes that can potentially create baffles in the reservoir.

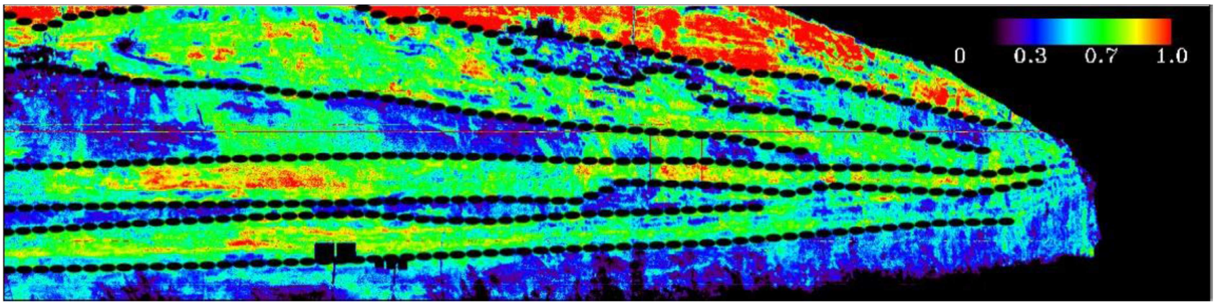


Figure 2: Kaolinite distribution map.

Acknowledgements: The authors acknowledge ANLEC and CTSCo for project support and constructive scientific debate.

References

KURZ, T.H., BUCKLEY, S.J. & HOWELL, J.A., 2011. Integration of panoramic hyperspectral imaging with terrestrial lidar data. *Photogrammetric Record*, 26(134): 212-228.

MURPHY, R., SCHNEIDER, S. & MONTEIRO, S.T., 2014. Mapping layers of clay in a vertical geological surface using hyperspectral imagery: variability in parameters of SWIR absorption features under different conditions of illumination. *Remote Sensing*, 6: 9104-9129.

RARITY, F., VAN LANEN, X.M.T., HODGETTS, D., GAWTHORPE, R.L., WILSON, P., FABUEL-PEREZ, I. & REDFERN, J., 2014. Lidar-based digital outcrops for sedimentological analysis: workflows and techniques. Sediment-Body geometry and heterogeneity: analogue for modelling the subsurface. *Geological Society, London, Special Publications*, 387: 153-183.

Utilisation of three-dimensional models in Exploration

Jens Grimsgaard[1*], Kristina B. Helland-Hansen[1], Ole J. Martinsen[2],
Simon Barker[1] & Trond Mjøs Johnsen[1]

[1] Statoil Research & Technology, Exploration Technology, P.O. Box 7200, N-5020 Bergen, Norway;
jegri@statoil.com; kheha@statoil.com,
[2] Statoil Exploration, Exploration Excellence, Bergen, Norway

Key words*: lidar, Google Earth, seismic modelling.*

Since the late 1990s Hydro/Statoil pioneered the development of virtual geology technology and the utilisation of outcrop data. Collected data were visualised and interpreted in virtual reality or co-visualised and interpreted with other data. Models were built and used as important analogues to better understand the subsurface data.

In Exploration, outcrops are extensively studied, and provide both a testing ground for new ideas, virtual field course assistance and quantitative analogues for existing exploration targets. There have been several studies aimed at collecting three-dimensional data from the more well-exposed outcrops, and these data have been used for various types of analysis, including sedimentological interpretation, structural measurement, and construction of synthetic seismic profiles. We will provide examples of our efforts in various locations, including integration of several three-dimensional outcrop models (photorealistic models), interpretations, and advanced synthetic seismic within the framework of GoogleEarth and proprietary extensions to it (Outcrop Digitizer).

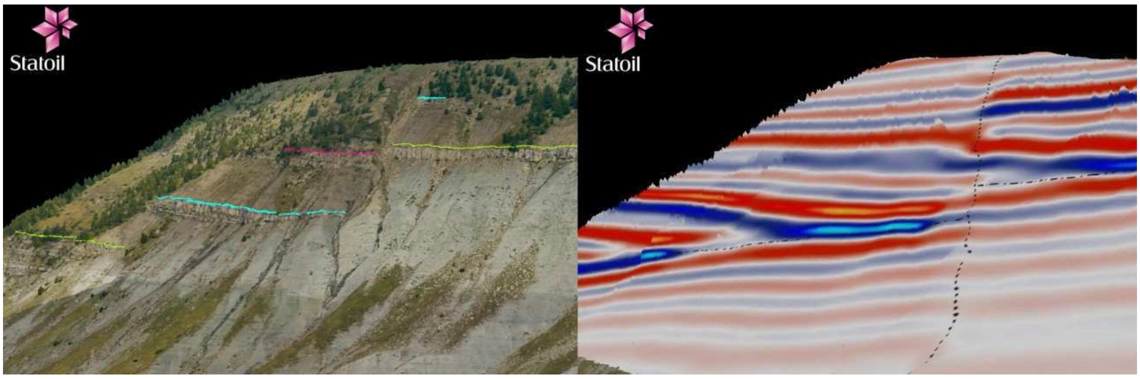


Figure 1: Left: Photorealistic 3D outcrop model (Chalufy, French Alps) acquired using laser scanning from helicopter. The outcrop with onlapping turbidite sandstones have quickly been digitized in an internal software package. Right: 25 Hz seismic model draped on top of outcrop.

Co-visualization of all data within an easy-to-use software package provides numerous benefits. It encourages cross-disciplinary interaction by combining observations into a single framework, allows field data to be kept in a single repository for easy access by end-users, and allows field trip and course participants to better understand the overall context of the outcrops they will be visiting both prior to and during a visit to the outcrops. We have also integrated HSE documentation into the virtual Google Earth projects to prepare the participants of the risks associated with the various locations to be visited. Some world class field localities have become inaccessible in both the short and long term. Weather, political and land owner issues have rendered some analogues inaccessible so virtual learning from these locations is the only option.

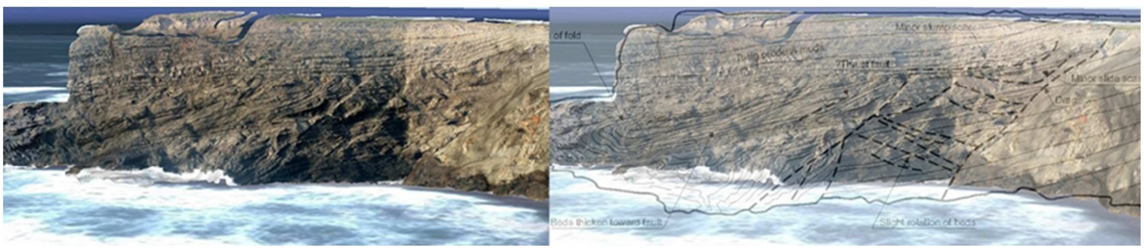


Figure 2: Left: Photorealistic 3D outcrop model from Western Ireland visualised in Google Earth. Right: A sketch from a publication placed in GE and made semi-transparent.

Lidar, photogrammetry & field measurements from Stackpole Quay: contrasting methods and implications for structural model building and prediction

Adam J. Cawood*, Clare E. Bond, John A. Howell & Yukitsugu Totake

Geology & Petroleum Geology, School of Geosciences, University of Aberdeen, Kings College,

Aberdeen AB24 3UE, UK; adam.cawood@abdn.ac.uk

Key words: *lidar, photogrammetry, model building, along-strike predictions.*

The use of geological data and observations from outcrops to gain an understanding of, and make predictions about, sub-surface structural geometries is a key process in the field of structural geology, with specific application to resource exploration. Often these outcrop studies are used to create maps and build cross-sections that together represent a 3D conceptual model of the structural geometries observed; and how these extend beyond the outcrop (into the sub-surface, or above ground). Virtual outcrops derived from techniques such as lidar and digital photogrammetry have the potential to provide large amounts of accessible, high resolution data for the construction of these 3D conceptual models. However, the efficacy of these techniques in characterising structural features when compared to traditional methods has not been tested.

Here we present a workflow for, and the results of, a quantitative analysis and interpretation of orientation data acquired using multiple technologies. The classic Stackpole Quay syncline outcrop (HANCOCK, 1979) in Pembrokeshire, is used to create two virtual outcrops, from lidar & digital photogrammetry. Structural data extracted from these virtual outcrops and directly from the structure, are quantitatively compared. Using this data, we build 2D and 3D geological models and use well established protocols (RAMSAY & HUBER, 1987) to make predictions of fold geometry along strike. Newly acquired data from the structure allows us to quantitatively assess the accuracy of our predictions.

We find that of primary importance are point matching and dense cloud generation algorithms during automated photogrammetric processing. Lidar derived point clouds display higher density and greater coverage of morphologically complex areas, allowing increased accuracy and fidelity of triangulated meshes to bedding plane orientations. Structural measurements extracted from virtual outcrops and derived models demonstrate the greater efficacy of lidar, when compared to digital photogrammetry, in making along strike predictions of fold shape and orientation. The geometric methods used for rigorous 3D model building require accurate structural data, and thus the faithful representation of geological structure in virtual outcrops is of key importance if they are to be used to build models and make predictions.

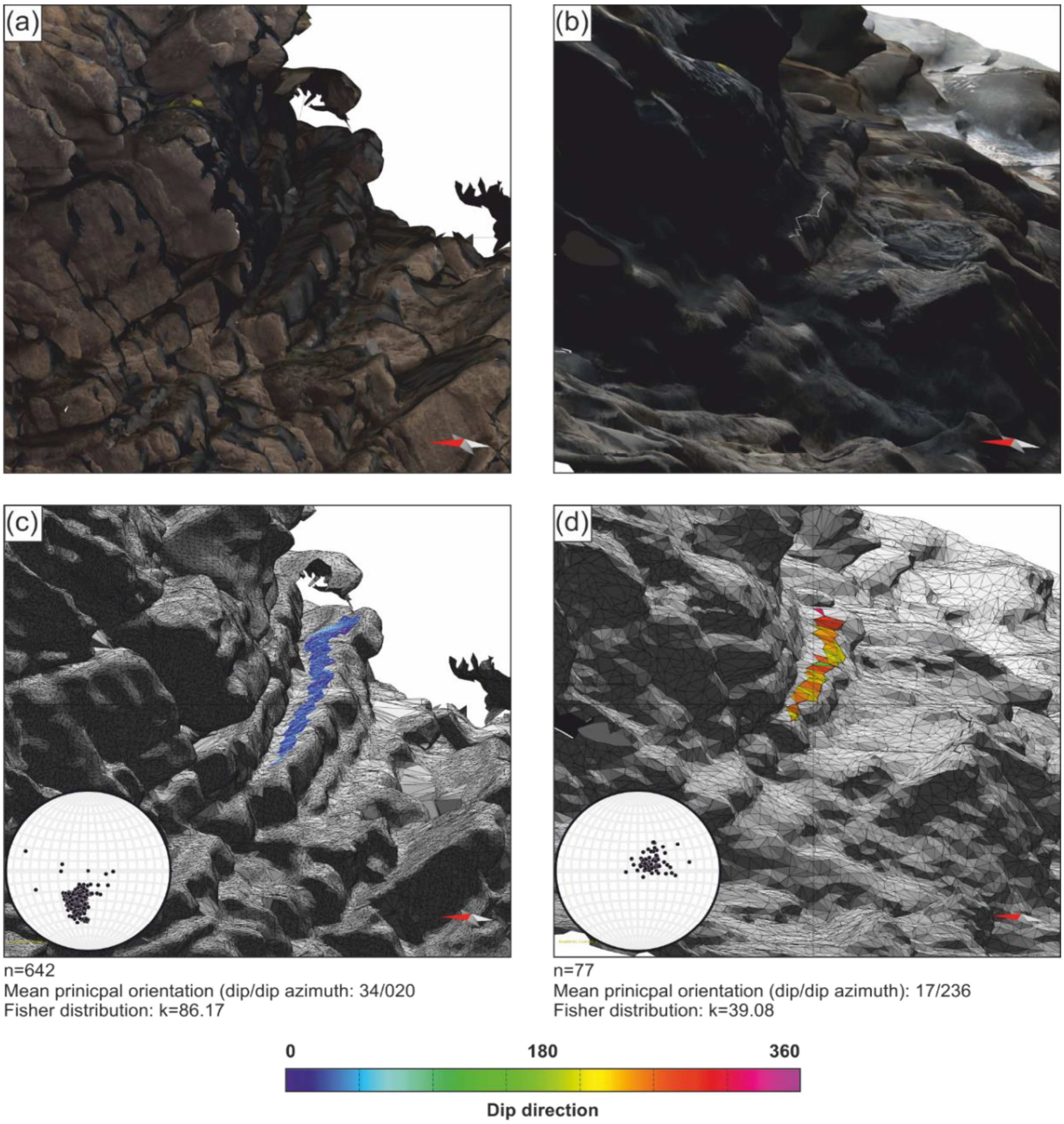


Figure 1: Detail of photorealistic (a) lidar and (b) digital photogrammetry derived virtual outcrops and untextured wireframe mesh surfaces of the same virtual outcrops for (c) lidar and (d) digital photogrammetry. Corresponding areas of virtual outcrops coloured by dip azimuth for comparison, with poles to bedding projected onto stereonets.

References

HANCOCK, P., 1979. Editorial: Background to the journal. *Journal of Structural Geology*, 1(1): 1-3.

RAMSAY, J.G. & HUBER, M.I., 1987. *The techniques of modern structural geology: Folds and fractures*. Academic press.

Session 11

Chair: Nick Rosser, Durham University

Terminus Forum

Friday 13:00 – 14:20, 23rd September

HPC implementation of image correlation techniques for monitoring slow-moving landslides with Sentinel-2 time series

André Stumpf[1,2], Jean-Philippe Malet[1,2], David Michéa[3], Fabrizzio Pacini[4] & Hervé Caumont[4]

[1] *IPGS – Institut de Physique du Globe de Strasbourg / Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, CNRS, 5 rue Descartes, F-67084 Strasbourg Cedex, France*
[2] *OSU EOST – Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, CNRS, 5 rue Descartes, F-67084 Strasbourg Cedex, France*
[3] *ICube – Laboratoire des Sciences de l'Informatique, de l'Ingénierie et de l'Imageir, CNRS, Pôle API, 300 Boulevard S. Brant, CS 10413, F-67412 Illkirch Cedex, France*
[4] *Terradue srl., Via Giovanni Amendola, 46, IT-00185 Rome, Italy.*

Key words: *change detection, landslides, registration.*

The increasing availability of optical satellite image time series (SITS) with very-high spatial resolution (e.g. Pléiades, Geoeye) and high temporal resolution (e.g. Sentinel-2, Landsat-8) offers enhanced possibilities for the detection and monitoring of landslides.

This includes not only the inventory mapping of rapid landslides after major triggering events but also the detection and monitoring of slow-moving landslides over wide areas. In particular image-correlation is a frequently used technique to measure horizontal surface displacement related to geomorphological and tectonic processes at sub-pixel precision from optical remote sensing images. It can overcome some of the limitations of interferometric SAR when the displacement exceeds 1/4 of the radar wavelength and the slope exposition is unfavourable relative to the line-of-sight geometry.

Despite the theoretical sub-pixel precision of available image correlation algorithms a number of potential error sources still often lead to false detections or biased measurements. Limitations can arise from imperfect sensor models, co-registration and orthorectification residuals, but also from study site characteristics such as the presence of a dense vegetation cover, cast shadows, low contrast areas and specular reflectance features. The availability of large optical SITS has the potential to improve the robustness and accuracy of the displacement measurements but there is currently a lack of scalable and easy-to-use techniques which allow full exploitation of large archived datasets and redundant measurements from optical SITS.

The presented study addresses this issue through the development and implementation of a new sub-pixel image processing chain for the detection and monitoring of slow-moving landslides. The underlying key idea is the possibility to obtain multiple, partially redundant displacement measurements through the analysis of multiple pair combinations within time series of optical images. The processing chain also includes routines for the elimination unreliable matches and the enhancement of the image co-registration. Time series of partially redundant displacement fields are combined to obtain i) reliable indicators for the presence of slow-moving landslides at very low false positive rates and ii) more accurate displacement time-series through spatio-temporal averaging.

Since redundant measurements with large image archives (e.g. Sentinel-2) and over wide areas require considerable computational resources, the processing chain makes use parallel and distributed computing on a cloud-based infrastructure. To this end the processing chain is based on the MicMac open-source library for image matching and implemented as a processing service on ESA's Geohazard Exploitation Platform (GEP) currently being implemented by Terradue srl.

Several use cases in the European Alps, Northern Apennines and the Ethiopian highlands show the effectiveness and efficiency of the processors for the detection and monitoring of large slow-moving landslides with Sentinel-2 and Landsat-8 time series.

Object-based change analysis of terrestrial laser scanning point clouds for shallow landslide monitoring

Andreas Mayr[1*], Martin Rutzinger[1,2], Magnus Bremer[1], Sander Oude Elberink[3], Clemens Geitner[1] & Thomas Zieher[1,2]

[1] *Institute of Geography, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria andreas.mayr@uibk.ac.at*
[2] *Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Technikerstr. 21a, 6020 Innsbruck, Austria*
[3] *Department Earth Observation Science, Faculty of Geo-Information Science and Earth Observation (ITC), University Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*

Key words: *lidar, geomorphology, erosion, segmentation, multi-temporal, change detection.*

Shallow landslides are gravitational mass movements of unconsolidated material on hillslopes with a maximum depth of about two meters. These dynamic processes are usually triggered by hydro-meteorological events, such as heavy rainfall events or rapid snowmelt. Shallow landslides affect infrastructure, cause a loss of soil and degrade agricultural land. Existing landslide scars typically remain active for years to decades, with retrogressive erosion at their scarps (i.e. clods of material slide or topple downward from the landslide scarp). The sliding mass can be reactivated by meteorological trigger events. Moreover, secondary erosion of already exposed areas by runoff, wind or snow movement can occur.

We present a point cloud-based approach to identify, monitor and describe changes on slopes affected by shallow landslides. The investigated test site is located in the Schmirn valley (Tyrol, Austria). It contains two shallow landslide scars that have been surveyed by terrestrial laser scanning (TLS) twice a year in early summer and autumn since 2011. The TLS point clouds are used to develop and test an approach for the multi-temporal 3D monitoring of landslides. At affected slopes the surface morphology of the landslides and their surroundings is complex and dynamic and changes in vegetation cover interfere with an automated analysis of geomorphic activity. This requires the use of advanced point cloud based techniques for both data pre-processing (e.g. for registration and vegetation filtering) and multi-temporal analysis. The change detection procedure employs a point-based segmentation of 3D landslide sub-objects. The unstructured points are grouped into segments according to their distance to each other and similarity measures. Such similarity measures can be radiometric properties of the scanned surface (i.e. laser pulse reflectance) or geometric features describing surface morphology (e.g. the direction of the normal vector to a locally fitted plane, local roughness, curvature, etc.). In a multi-temporal analysis these segments are handled as moving and deforming objects to track their changes in 3D. Extracting geomorphologically-meaningful objects that can be recognised and correctly matched in consecutive scans is challenging due to the objects' fuzziness in reality and the lack of unique and consistent patterns in a feature space. However, our results indicate that with this object-based approach discrete parts of the landslide, such as individual clods of soil, can be monitored. For instance, their three-dimensional movement or their disintegration within time steps can be observed, resulting in a comprehensive characterization of the landslides' evolution during the monitoring period.

Identified changes of the two shallow landslide scars at the test site are interpreted to enhance the understanding of landslide kinematics and mechanisms of secondary erosion. The landslides' evolution between successive scans is analysed together with meteorological data, recorded by a nearby weather station, to investigate the role of e.g. heavy precipitation events.

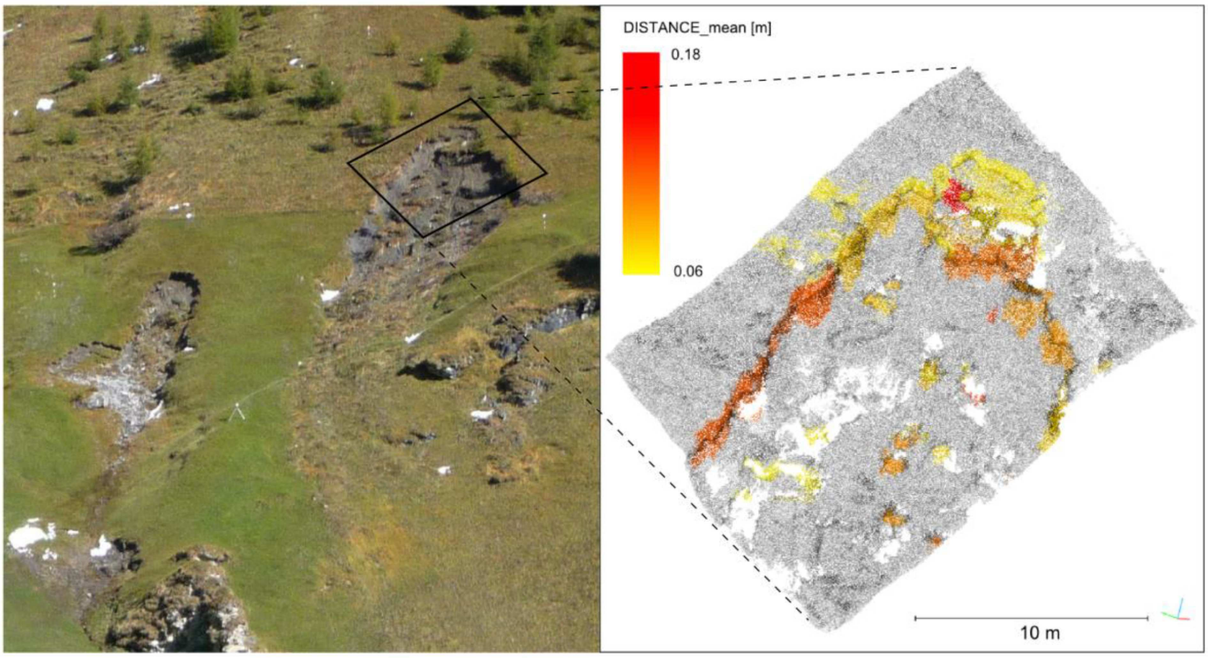


Figure 1: Left: The two investigated landslide scars. Right: Changes in the upper part of a landslide scar (October 2011 to May 2012). Segments are coloured by mean cloud-to-cloud distance per segment.

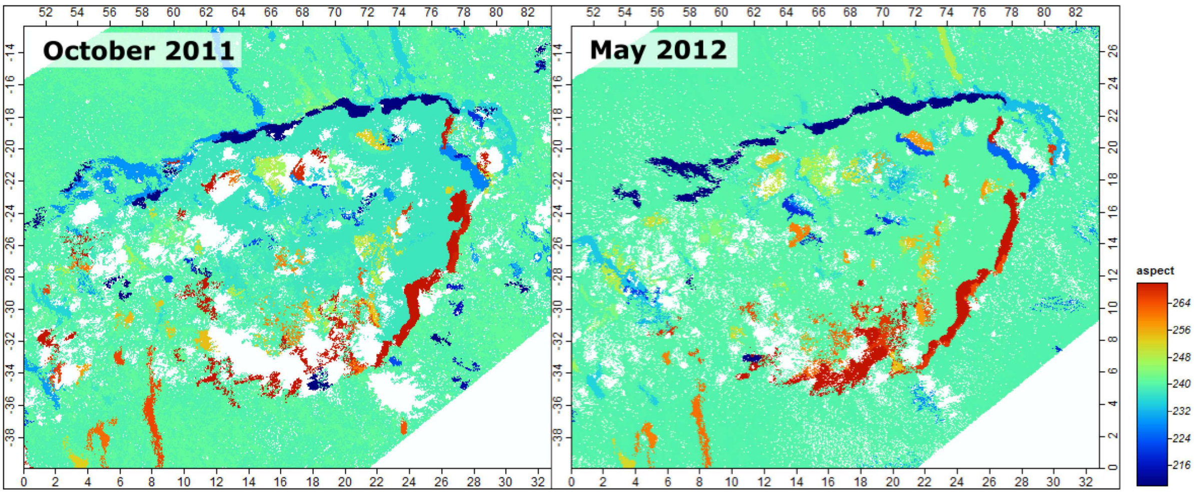


Figure 2: A landslide scar in two consecutive scans with point cloud segments coloured by segment aspect.

Acknowledgements: This work is funded by the Doctoral Fellowship Programme of the Austrian Academy of Sciences.

Quantification of intact rock bridges and rock mass fragmentation after failure by means of remote sensing techniques

Margherita Cecilia Spreafico[1], Francesca Franci[1*], Gabriele Bitelli[1],
Lisa Borgatti[1] & Monica Ghirotti[2]

[1] DICAM - University of Bologna, Viale del Risorgimento 2, Bologna, Italy; francesca.franci2@unibo.it
[2] University of Ferrara, Via Saragat 1, Ferrara, Italy.

Key words: *rock bridges, fragmentation, terrestrial laser scanner, UAVs.*

In this work, two processes related to the onset and the evolution of large-scale rock falls-topples have been analysed by means of remote sensing techniques. On the one hand, the number of rock bridges vs pre-existing fractures have been estimated in a newly-formed landslide scarp. On the other hand, the fragmentation of the rock mass after failure was assessed.

The characterization of discontinuity persistence and intact rock bridges is one of the main challenges of rock mechanics. Several authors have tried to quantify and incorporate rock bridges in stability analyses; an overview can be found in TUCKEY (2012).

One of the most evident differences between fresh and pre-existing weathered fractures in a newly-formed landslide scarp is the colour, due to hydro-chemical processes. Amongst others, FRAYSSINES & HANTZ (2007) and PARONUZZI & SERAFINI (2009) used this feature to estimate rock bridges area.

A semi-automatic approach, based on the degree of weathering, i.e. iron oxide coatings or staining along fractures, and thus on the different colour of the discontinuities, is proposed and tested on the scar of the recent San Leo 2014 failure. Here, a calcarenitic rock mass was involved in a toppling phenomenon, with a scarp area in the order of 20000 m^2. The estimation of the rock bridges percentage was conducted on a coloured terrestrial laser scanner (TLS) point cloud of the failure scar, acquired few days after the failure (Fig.1).

In order to minimize the effects of the presence of humidity on the cliff, of the light condition during the acquisition and of the occlusions, the same procedure was repeated on a UAV point cloud acquired few weeks after the failure. Based on the results, the location and the orientation of the pre-existing fractures were investigated. The estimated number of rock bridges in the scar is in agreement with the one inferred using numerical modelling techniques, in the order of 50% of the scarp surface.

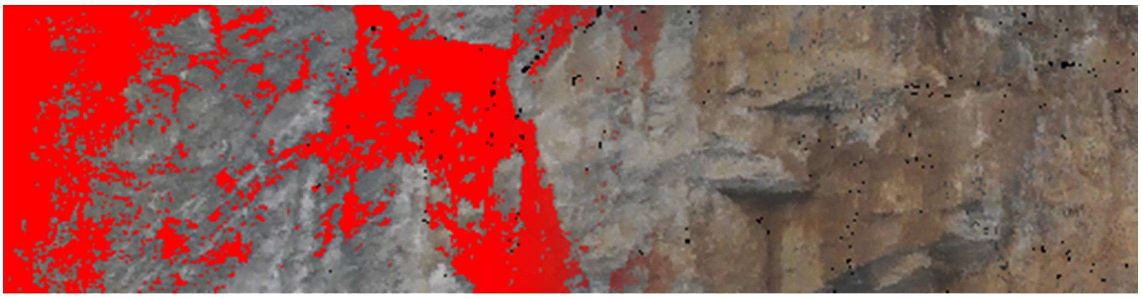


Figure 1: coloured terrestrial laser scanner point cloud. On the left side of the picture the individuated pre-existing discontinuities are highlighted in red.

After failure, the fragmentation of the rock blocks can occur through (a) the breaking of intact rock, (b) the failure along pre-existing discontinuities and (c) a combination of the previous two. The comparison between the number of fresh fractures formed during failure and the one measured in the landslide deposit, i.e. after the impact between falling blocks and/or on the ground surface, can assist in the determination of the fragmentation occurring in the failed rock mass after the detachment phase.

The procedure was applied to the orthophoto of the landslide deposit, by means of an object-based classification. This approach, classifying groups of image pixel based on features such shape and texture, coupled with spectral characteristics, permitted firstly to map the blocks in the deposit area (FRANCI & SPREAFICO, 2016) and subsequently to assign their surfaces to different classes representing newly formed or pre-existent discontinuities.

The variation of the intact rock bridge amount was estimated by comparing the percentage of newly formed fractures in the scarp and in the deposit area.

Acknowledgements: the authors wish to thank the Emilia-Romagna Region (STB Romagna) for the San Leo orthophoto.

References

FRANCI, F. & SPREAFICO, M.C., 2016. Processing of remote sensing data for the estimation of rock block size distribution in landslides deposits. *Proceedings of the 12th International Symposium on Landslides*, June 12th-19th 2016, Naples.

FRAYSSINES, M. & HANTZ, D., 2007. Failure mechanisms and triggering factors in calcareous cliffs of the subalpine ranges (French Alps). *Engineering Geology*, 86(4): 256-270.

PARONUZZI, P. & SERAFINI, W., 2009. Stress state analysis of a collapsed overhanging rock slab: A case study. *Engineering Geology*, 108(1-2): 65-75.

TUCKEY Z.S., 2012. An integrated field mapping-numerical modelling approach to characterising discontinuity persistence and intact rock bridges in large open pit slopes. M. Sc. Theses, Simon Fraser University, Vancouver.

Development of a TLS real-time monitoring system for landslides

Ryan A. Kromer[1,2*], Antonio Abellan[1,2,3], Jean Hutchinson[2], Matt Lato[4], Marie-Aurelie Chanut[5] & Michel Jaboyedoff[1]

[1] *Risk Analysis Group, University of Lausanne, Lausanne, Switzerland, ryan.kromer@unil.ch*
[2] *Geomechanics Group, Queen's University, Kingston, Ontario, ryan.kromer@queensu.ca*
[3] *Scott Polar Research Institute, Cambridge, UK*
[4] *BGC Engineering, Ottawa, Canada*
[5] *Groupe Risque Rocheux et Mouvements de Sols (RRMS), Cerema Centre-Est, France*

Key words: *lidar, TLS, automatic point cloud processing, real-time monitoring.*

Monitoring slope instabilities and landslides with remote sensing approaches forms an important part of many risk management strategies. Remote monitoring can be challenging given difficult site access, bulky monitoring equipment and low project budgets. Additionally, quick installation is sometimes required for a temporary monitoring campaign. A promising alternative to slope radar and GB-InSAR technologies is using a terrestrial laser scanner (TLS) as a light, portable, cost-effective temporary or permanent landslide monitoring solution. Such systems require automation of the data collection and processing workflow given the vast amounts 3D data collected. In this study we address the development of both the hardware and software components of such a system.

We built a wooden encasement to house an Optech Ilris long range TLS (see Fig. 1) and anchored it to the first level of a concrete building overlooking the Séchilienne rockslide in the French Alps (HELMSTETTER & GARAMBOIS, 2010). Within the encasement, the TLS is mounted on a manual pan tilt allowing adjustment of the view angle. Data processing is conducted on site using a field laptop within the building. The laptop is connected to the local cellular network allowing for remote operation of the scanner and remote access to the processed results.

Figure 1: Field setup of the real time TLS monitoring system using Optech Ilris LR scanner.

The software component of the system consists of modules to operate the scanner, to manage and backup data, and automatically treat the data. The data processing module was developed in-house using C++ with QT and the Point Cloud Library (RUSU & COUSINS, 2011) and is outlined in Fig. 2. The first step of the algorithm is removal of unwanted points and a quality control (QC) step. Unwanted points are removed using a pass-through filter and the QC step consists of rejection of a point cloud if it does not contain a specified number of points, which is commonly due to poor atmospheric conditions or rainfall. The second step is registration of the point cloud to a reference through a registration pipeline consisting of an optional initial alignment stage followed by an iterative fine alignment stage. The optional initial alignment consists of finding repeatable key points in the point cloud, defining descriptors based on the local key point neighbourhoods and finding correspondences between features to perform an initial transformation. Refined alignment is conducted by iteratively transforming the point cloud, finding correspondences and using a rejector pipeline to discard poor correspondences until a convergence criterion is met. Change detection is conducted by calculating slope dependent change vectors and filtering noise using neighbours in space and time (KROMER *et al.*, 2015).

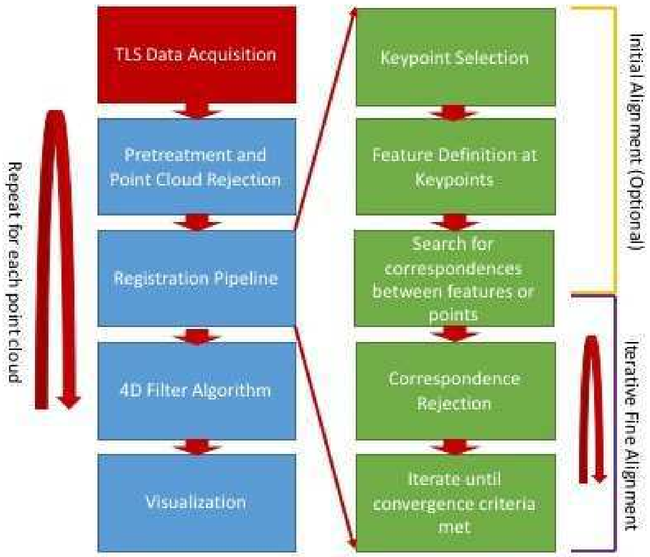


Figure 2: Automatic TLS data acquisition and automatic data processing.

Initial testing of the system reveals that the data treatment on the laptop is faster than the 10 KHz data acquisition rate, allowing near real time analysis and visualisation of change. This system can be a viable alternative to GB-InSAR monitoring given its relatively lower operating cost, ease of setup and high-resolution point representation of the terrain.

Acknowledgements: We would like to acknowledge the Centre for studies and Expertise on Risks, Environment, Mobility, and Urban and Country planning (CEREMA) for allowing installation of the TLS on their monitoring centre.

References

HELMSTETTER, A. & GARAMBOIS, S., 2010. Seismic monitoring of Séchilienne rockslide (French Alps): Analysis of seismic signals and their correlation with rainfalls. *Journal of Geophysical Research: Earth Surface*, 115 (F3).

KROMER, R.A., ABELLÁN, A., HUTCHINSON, D.J., LATO, M., EDWARDS, T. & JABOYEDOFF, M., 2015. A 4D filtering and calibration technique for small-scale point cloud change detection with a terrestrial laser scanner. *Remote Sensing*, 7: 13029-13052.

RUSU, R.B. & COUSINS, S., 2011. 3D is here: Point Cloud Library (PCL). *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, Shanghai: 1-4.

Session 12

Chair: Nicole Naumann, Uni Research

Terminus Hall

Friday 14:50 – 15:30, 23rd September

Surface kinematics of periglacial sorted circles over 8 years using SfM close range photogrammetry

Andreas Kääb[1*], Luc Girod[1] & Ivar Berthling[2]

[1] Department of Geosciences, Univ. of Oslo, PO Box 1047, 0316 Oslo, Norway, kaeaeb@geo.uio.no
[2] Department of Geography, Norwegian University of Science and Technology, Trondheim, Norway

Key words: *SfM photogrammetry, patterned ground, sorted circles, permafrost, Svalbard.*

Sorted soil circles are a form of periglacial patterned ground that is commonly noted for its striking geometric regularity. They consist of an inner fine domain bordered by gravel rings that rise some decimetres above the fine domain. Field measurements and numerical modelling suggest that these features develop from a convection-like circulation of soil in the active layer of permafrost. The related cyclic burial and exhumation of material is believed to play an important role in the soil carbon cycle of high latitudes. The connection of sorted circles to permafrost conditions and its changes over time make these ground forms potential palaeoclimatic indicators. In this study, we apply the photogrammetric structure from motion (SfM) method (KÄÄB *et al.*, 2014) to large sets of overlapping terrestrial photos taken in Augusts of 2007, 2010 and 2015 over three sorted circles at Kvadehuksletta, western Spitsbergen. In 2015 we used a modified acquisition setup and a new camera to push resolution and precision even further compared to the 2007 and 2010 data. We retrieve thus repeat digital elevation models (DEMs, Fig. 1) and ortho-images with millimetre to sub-millimetre resolution and precision. Changes in microrelief over the 8 years are obtained from DEM differencing (Fig. 1) and horizontal displacement fields from tracking features between the ortho-images (Fig. 1). In the fine domain, surface material moves radially outward at horizontal rates of up to ~2 cm yr^{-1}. The coarse stones on the inner slopes of the gravel rings move radially inward at similar rates. A number of substantial deviations from this overall radial symmetry, both in horizontal displacements and in microrelief, shed new light on the spatio-temporal evolution of sorted soil circles, and potentially of periglacial patterned ground in general. The extension of our initial 2007-2010 period to a third epoch, 2015, enables us to draw first conclusions about the temporal variability of the sorted-circle kinematics obtained. Our results also demonstrate the large potential of SfM in general to investigate Earth surface processes at local scales with unprecedented precision and resolution – and with very limited effort.

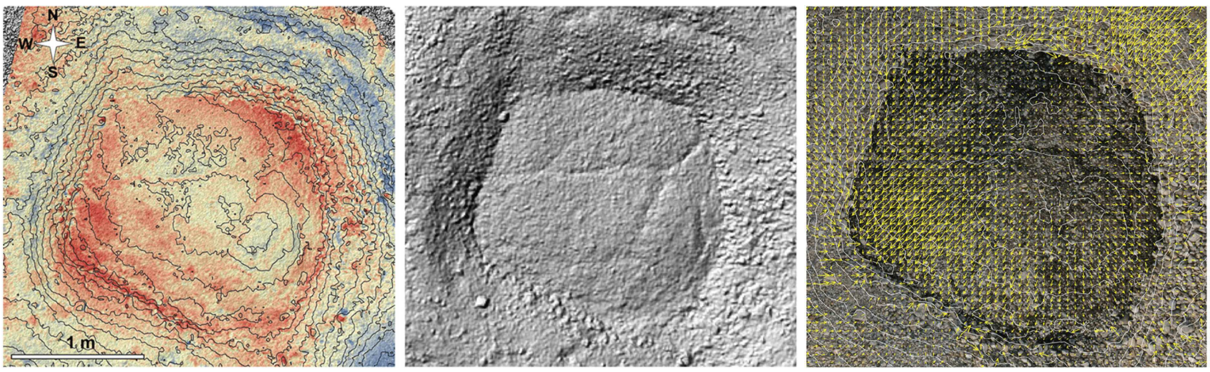


Figure 1: Sorted Circle on Kvadehuksletta, Spitsbergen. Left: elevation differences 2007-2010 (± 3 cm/yr); middle: hillshade; right: horizontal velocities 2007-2010 of up to 2.5 cm/yr.

Acknowledgements: European Research Council under the European Union’s Seventh Framework Programme, Svalbard Science Forum, Research Council of Norway. The software MicMac was kindly provided by the French National Institute of Geographic and Forest Information (IGN).

Reference

KÄÄB A., GIROD L. & BERTHLING I., 2014. Surface kinematics of periglacial sorted circles using structure-from-motion technology. *Cryosphere*, 8: 1041-1056.

The application of UAV acquired photogrammetric models in natural disaster mitigation: Volcanic monitoring and crowd-sourced flood modelling

John Howell[1], Dougal A. Jerram[2,3], Sarah Gordee[2], Clare Bond[1], Magda Chmielewska[1], Rob Butler[1] & Jose Puig[1]

[1] University of Aberdeen, Aberdeen UK; john.howell@abdn.ac.uk
[2] DougalEarth Limited,
[3] CEED, University of Oslo, Norway

Key words: *SfM photogrammetry, thermal, visualisation, registration.*

The advent of high quality, low cost UAVs (drones), coupled with recent developments in photogrammetric processing software has seen a surge in applications for the Earth Sciences. The acquisition of Virtual Geological Outcrops (VOs) has become almost routine, and the earth science community is continually inventing new ways to utilise these data. In this contribution we present two cases studies which illustrate novel applications of these methods, which we believe have far-reaching implications for disaster mitigation.

Volcanos represent a continuous and well-known natural hazard to millions of people around the world. Volcanic monitoring is required to predict the exact timing of eruptions in order to facilitate evacuation of nearby settlements. This monitoring typically involves the placement of a network of seismic recording devices, as well as other instruments, across the volcano, a process which is expansive and potentially hazardous. In addition to seismic monitoring, satellite altimetry is sometimes used to record small scale changes in the topography of the volcano which may represent a prelude to an eruption.

In October 2015, preliminary field trials were undertaken on Stromboli, an active volcanic island off the coast of Sicily. These trails involved flying two UAVs across the crater of the volcano. The first was used to record a set of 250 regular photographs which were used to build a photogrammetric DEM of the crater with a vertical and horizontal resolution of 0.1m. The second UAV was fitted with a FLIR IR camera and was used to acquire a comparable set of thermal images. Ground control points were measured with a dGPS, these were marked with burning torches so that they could be identified on the thermal imagery. The IR imagery was then draped over the DEM to produce a 3D thermal model of the volcano. In addition to the active vents, this model also highlighted a number of thermal anomalies on the flanks of the volcano which are interpreted to be related to lava flows from the last major eruption in August 2014, and show the longevity of cooling of these types of events.

In the future, repeat surveys could be used to monitor subtle changes in both the surface topography and heat flow of the volcano, providing a low cost, low impact and safe monitoring program.

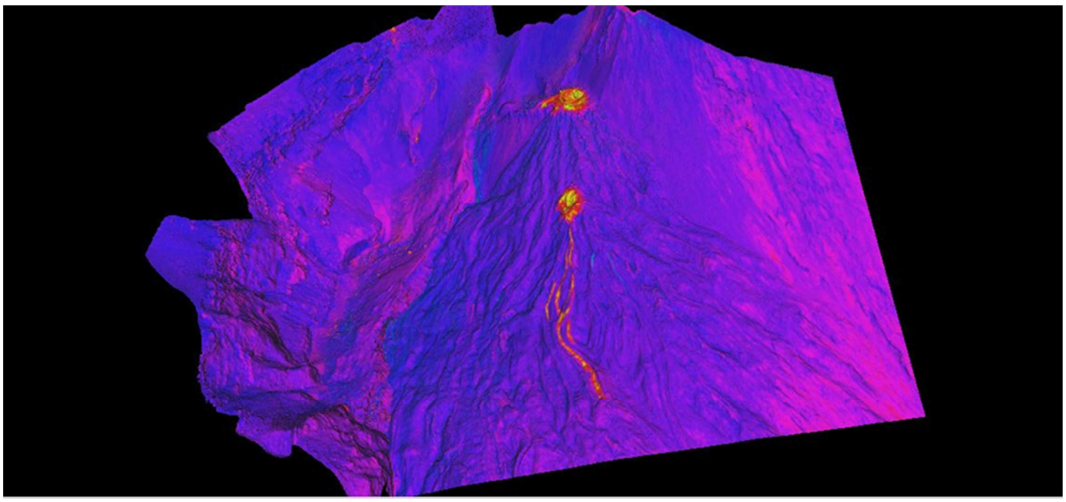


Figure 1: Thermal 3D model of the east flank of Stromboli. Warm areas include two active craters and a series of lava flows from the 2014 eruptions.

The second case study is from the 2015/16 floods that affected north-east Scotland. During storm Frank (30th Dec 2016) run-off from severe rainfall in the Dee Valley caused major flooding which significantly impacted homes and infrastructure in the region including the village of Aboyne, where floodwaters backed up behind an elevated causeway across the floodplain causing significant flooding in the town and erosion and scour beneath the bridge arches that almost resulted in its failure.

A major challenge to modelling and managing such floods is the lack of detailed hydrographic data away from a few selected gauging stations along the river. In the case of Aboyne, river levels from either side of the bridge are required to model the flow through the arches in order to mitigate against the scour and erosion that occurred during the flood.

Five days after the event a UAV was used to acquire a detailed DEM across the area around Aboyne. This model was calibrated using a Leica dGPS to give a resolution of 0.1 m in XY and Z. The model covers an area of 700 m^2 and is based on a point cloud of 1703795 points. Both the scouring under the bridge and the redistribution of sediment on the flood plain downstream are captured in the elevation model.

In order to create the hydrographs, a social-media campaign was used to crowd source digital imagery taken during the floods by the public. Significant mainstream media coverage resulted in over 1,000 images and videos being submitted by the public, of which 773 came from the area of interest. Time stamps captured with the images were used to sort them into a time series. Flood levels on prominent features such as buildings, walls, fences and roads within the images were used to determine river levels through the flood event. Once these were identified in the DEM it was possible to contour the change in river level through time. The resulting 3D hydrograph shows the build-up of water on the up-stream side of the bridge that resulted in its under-mining during the flood. The new hydrograph is being used to model bed erosion and sediment deposition for the flood and to inform policy makers on flood mitigation strategy.

The resultant hydrograph is the first known to be created from crowd-sourced data. The hydrographs are far more localized than the existing gauging stations and provide essential inputs to modelling. They also promote science within the community. For future flood warning and infrastructure management a solution that allows a real-time hydrograph to be created utilising augmented reality to integrate the river level information in crowd sourced imagery directly onto a 3D model, would significantly improve management planning and infrastructure resilience assessment.

Figure 2: Flooding in Aboyne. Images such as the upper left can be used to recreate a hydrograph by superimposing flood levels on the DEM (lower). The results can be used to model the impact of flood related scour under the bridge (upper-right).

Poster session

Chair: Tobias Kurz
Uni Research

Thursday 16:05 – 18:15, 22nd September

An evaluation of low-cost consumer-grade UAS systems for 3D reality capture

Dietmar J. Backes[1*], Oliver Teasdale[1] & Jacques Eloff[2]

[1] *UCL - CEGE, Gower Street, London WC1E 6BT, United Kingdom; d.backes@ucl.ac.uk*
[2]*Vertech Imaging, Cobham, Surrey KT11 2LJ, United Kingdom*

Key words: *photogrammetry, SfM, UAVs, validation.*

During the last years small, lightweight and low-cost remotely piloted aerial systems (RPAS), commonly referred to as drones, have rapidly developed into capable low cost unmanned aerial systems (UAS). Fuelled by a vibrant community of scientists, professionals and hobby enthusiasts enabling technologies have matured rapidly and prices of consumer-grade as well as semi-professional systems fell sharply.

Especially multirotor vertical take-off and landing (VTOL) UAS have proven to be versatile and flexible platforms which can be equipped with a range of sensors capable to capture aerial data for a variety of 2D and 3D mapping applications. Consumer-grade, low weight systems such as the DJI Phantom or 3DR Solo have a limited payload and are equipped with low weight action cameras like the GoPro Hero models which are capable to collect video as well as still RGB and near-infrared imagery. Applying traditional photogrammetric methods to imagery from low-cost UAS systems proved complex and impractical in the past. However, modern state-of-the-art structure from motion algorithms implemented in off-the-shelf software packages (sometimes referred to as the new photogrammetry), cloud processing environments and available via open source libraries promise to generate dense 3D point clouds, textured models and ortho-images in high quality and with little effort. How accurate and how reliable are data products generated from such systems?

Expanding from a preliminary study (BACKES & TEASDALE, 2015) we review the progressing capabilities and features of COTS (commercial of the shelf) user and semi-professional UAS systems under the aspects of deployable sensors, ease of use, reliability as well as safety. We show the workflow from flight planning, data collection to dense point cloud matching using a range of software products. The resulting point clouds are evaluated and benchmarked using highly accurate and dense reference data acquired via geodetic terrestrial survey and laser scanning. The results of this evaluation allow conclusions on the current accuracy capabilities of such low-cost systems.

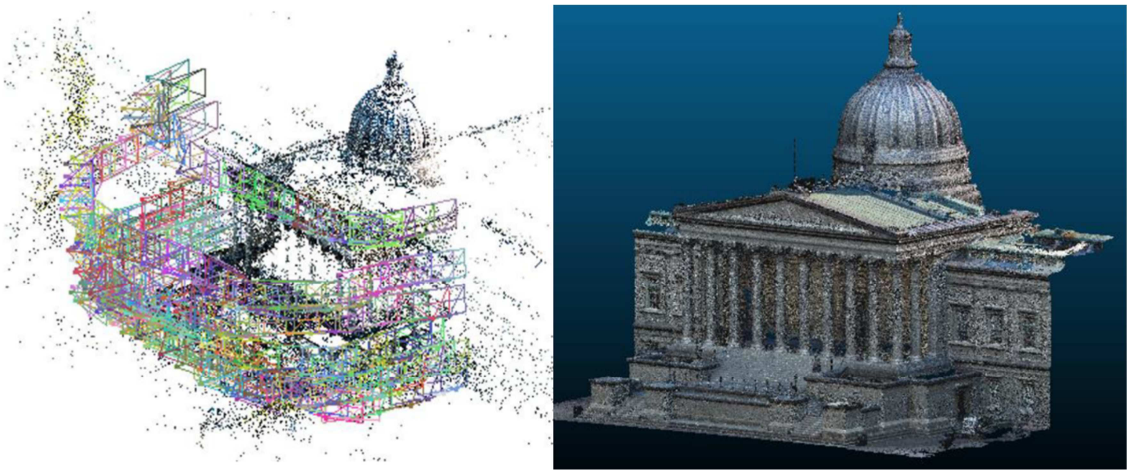


Figure 1: UAS benchmark test around the UCL Portico. Left: Camera locations and orientations; right: matched 3D point cloud.

Reference

BACKES, D. & TEASDALE, O., 2015. Evaluation of low cost consumer grade UAS systems for 3D reality capture and mapping, *GRSG Challenges in Geological Remote Sensing* 2015.

Investigating snow cover volumes and icings dynamics in the moraine of an Arctic catchment using UAV/photogrammetry and lidar

Éric Bernard[1*], Jean Michel Friedt[2], Christelle Marlin[3], Florian Tolle[1], Madeleine Griselin[1] & Alexander Prokop[4]

[1] *TheMA/CNRS, University of Franche Comté, Besançon, France; eric.bernard@univ-fcomte.fr*
[2] *FEMTO-ST, University of Franche Comté, Besançon, France*
[3] *GEOPS UMR 8148, CNRS - University of Paris Sud, France*
[4] *UNIS, Longyearbyen, Norway*

Key words: *Arctic, photogrammetry, UAVs, SfM, snow cover, geomorphology, proglacial moraine.*

Means for assessing the contribution of the terminal moraine into the water budget of an Arctic glacier is investigated: on the one hand the terminal moraine represents a significant fraction (22%) of the catchment area of the glacier under investigation – Austre Lovenbreen, in the Brøgger peninsula, Spitsbergen (BERNARD *et al.*, 2013) – and on the other hand icings formation (or *aufeis*) each winter illustrates the contribution of subglacial water flow. While over the glacier, with a smooth surface readily interpolated, the winter and summer mass balances are assessed with only a few sparsely distributed stakes, such an approach is not valid with the rough topography of the glacier moraine: high spatial resolution elevation models at different seasons are needed to estimate the volume of ice and snow accumulated during winter in this part of the catchment basin and released in rivers during the melting season. Even if located at only 6 km from the Ny-Ålesund meteorological station, the moraine of Austre Lovenbreen catchment can collect snow whose amount may differ from that given by station, due to drift snow and elevation-amount gradient, with spatial and temporal variability. Surveying the terminal moraine by remote sensing methods is helpful for better quantifying the snow cover in proglacial moraines.

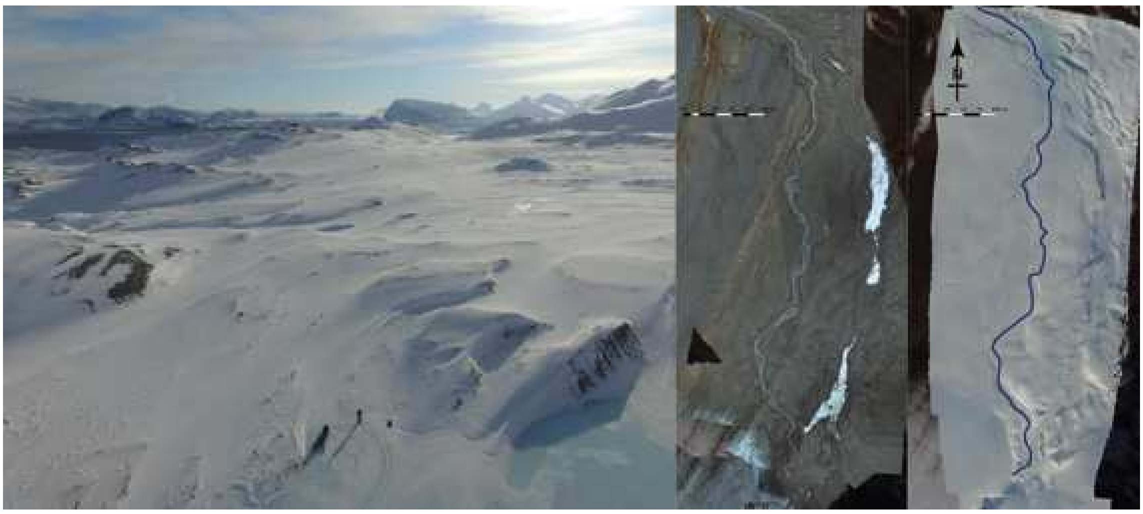


Figure 1: Oblique view of the study area and comparison of September (left) and April (right) stream channel resulting from subglacial outflow (Austre Lovenbreen).

Lidar – and in our case its terrestrial implementation – is currently the reference system for digital elevation model (DEM) generation: this highly specialized instrument provides utmost resolution with the drawback, when considering extended terminal moraine areas, of excessive shadows avoided by bringing the instrument to elevated measurement positions, a feat not necessarily achievable in given weather conditions or geographic settings. We consider the complementary use of a commercial off the shelf (COTS) DJI Phantom3 Professional unmanned aerial vehicle (UAV) for aerial photography acquisition (LUCIEER *et al.*, 2014), combined with structure from motion (SfM; WESTOBY *et al*., 2012 – using dedicated software such as MicMac, IGN, Agisoft PhotoScan and QGis) analysis, for DEM computation: DEM differences between datasets acquired in April (snow cover maximum and icings volume maximum) and September (snow cover minimum) yield a volume difference attributed either to snow cover or icings formation. Repeat measurements over a short interval on moraine regions where topography is known to be stable, hint at an elevation resolution in the decimetre range – far better than the icings and snow accumulation in the meter range. While the vegetation-free moraine provides ideal conditions for SfM – with lateral resolution down to 5 cm/pixel when flying at an altitude of 100 m – snow and river ice covered areas are challenging for the feature matching step needed for SfM initialization. We observe that with appropriate lighting conditions, avoiding long shadows associated with a low-lying sun and overcast weather conditions, well resolved DEMs are acquired and generate a useful dataset for analysis.

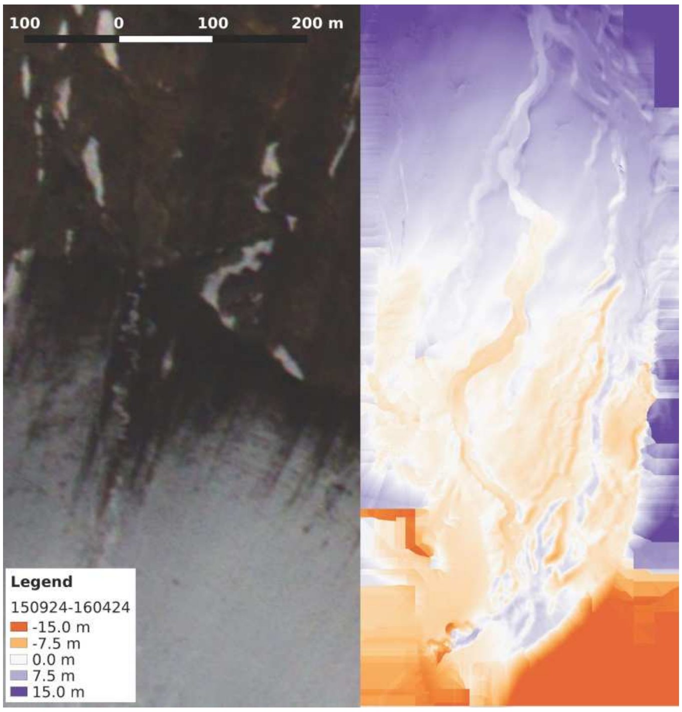


Figure 2: DEM difference between April and October acquisition. The result is mapped on a Formosat satellite image, which is used as a spatial reference.

This presentation shows early applications on snow accumulation over the moraine, and on icing volume estimation, which provides a significant water reservoir. In a next step, the goal is to compare water equivalent accumulation (W.Eq.) in the icing with constant outflows monitored on the outlet of the basin.

Acknowledgements: French National Centre for Research, Franche Comté region, IPEV, Photocoptère.

References

BERNARD, É., FRIEDT, J.M., TOLLE, F., GRISELIN, M., MARTIN, G., LAFFLY, D., & MARLIN C., 2013. Monitoring seasonal snow dynamics using ground based high-resolution photography (Austre Lovénbreen, Svalbard, 79°N). *ISPRS Journal of Photogrammetry and Remote Sensing*, 75: 92-100.

LUCIEER, A., TURNER, D., KING, D.H., & ROBINSON, S.A., 2014. Using an Unmanned Aerial Vehicle (UAV) to capture micro-topography of Antarctic moss beds. *International Journal of Applied Earth Observation and Geoinformation,* 27: 53-62.

WESTOBY, M.J., BRASINGTON, J., GLASSER, N.F., HAMBREY, M.J., & REYNOLDS J.M., 2012. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179: 300-314.

GB-InSAR and terrestrial laser point clouds for characterising the transient deformation pattern of a large gravitational instability during rainfall events

Pierrick Bornemann[1,2], Floriane Provost[2], Jean-Philippe Malet[2], Gilbert Ferhat[2], Zarina Acero[2], Maxime Vieville[3] & Catherine Bertrand[3]

[1] *LIVE – Laboratoire Image, Ville, Environnement, Université de Strasbourg, CNRS, 3 rue de l'Argonne, F-67083 Strasbourg Cedex, France*

[2] *IPGS – Institut de Physique du Globe de Strasbourg / Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, CNRS, 5 rue Descartes, F-67084 Strasbourg Cedex, France*

[3] *OSU-THETA – Chrono-Environnement, CNRS / Université de Bourgogne-Franche-Comté, 16 route de Gray, F-25030 Besançon Cedex, France*

Key words: *landslide, radar, lidar, change detection.*

The Séchilienne landslide is located on the right bank of the Romanche River, south east of Grenoble (Isère, France). The active zone of the gravitational instability involves several millions of cubic meters. The geology consists of fractured hard rocks (micaschists) with double permeability and strong spatial heterogeneities. The deformation of the unstable slope is monitored by on-site extensometric gauges, inclinometers, GNSS and at distance by terrestrial radar and a total station.

Over the last decades, ground based radar interferometry (GB-InSAR) and terrestrial laser scanning (TLS) have been successfully used for the reconstruction of landslides surface displacement fields. Both techniques have complementary characteristics in terms of results accuracy and spatio-temporal resolution, which makes their integration suitable for a system of surface displacements detection and monitoring.

In this work, we aim at comparing and integrating surface displacement measurements obtained from simultaneous GB-SAR and TLS acquisitions over the Séchilienne rockslide (French Alps) during a campaign of three weeks in May 2016. Both datasets consist of repeated surveys from the same base station with a high temporal resolution (2 minutes for the GB-SAR dataset, and one per week for the TLS dataset), acquired respectively with an IBIS-L terrestrial SAR interferometer and with an Optech ILRIS 3D TLS sensor.

The datasets are processed separately in order to produce landslide surface displacement maps during the experiment. Computed displacements are compared in order to identify the most active areas and to assess the transient deformation pattern of the slope in relation to rainfall events.

Results from GB-SAR and TLS differ greatly in terms of spatial resolution, accuracy and dimensionality (e.g. GB-SAR only has the ability to compute 2D displacements, and produces less spatially dense results than TLS, but is able to detect smaller displacements), which justifies the development of an integrative framework, based on a common georeferencing of 2D and 3D results, using the dataset complementary characteristics for a better understanding of the slope dynamics.

Point cloud time series for monitoring landslide processes: Displacement field analysis using image correlation and optical flow algorithms

Pierrick Bornemann[1,2], Antoine Guérin[3], Jean-Philippe Malet[2], Cindy Vulliez[3], Julien Travelletti[4], Anne Puissant[1], Marc-Henri Derron[3], Michel Jaboyedoff[3], Marie-Aurélie Chanut[5] & Laurent Dubois[5]

[1] *LIVE – Laboratoire Image, Ville, Environnement, Université de Strasbourg, CNRS, 3 rue de l'Argonne, F-67083 Strasbourg Cedex, France*
[2] *IPGS – Institut de Physique du Globe de Strasbourg / Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, CNRS, 5 rue Descartes, F-67084 Strasbourg Cedex, France*
[3] *ISTE - Institut des Sciences de la Terre, Faculté des géosciences et de l'environnement, Université de Lausanne, Geopolis, CH-1015 Lausanne, Switzerland*
[4] *BEG – Bureau d'Etudes Géologiques SA, Rue de la Printse 4, CH-1994 Aproz, Switzerland*
[5] *CEREMA – Direction territoriale Centre-Est, Cité des Mobilités, 25 Avenue François Mitterand, CS92 803, F-69674 Bron Cedex, France.*

Key words: *natural hazards, photogrammetry, lidar, matching, change detection.*

Time series of dense three-dimensional point clouds have proved useful for long-term monitoring of the structure and kinematics of slope movements. However, such datasets are large and complex and require accurate and efficient processing methods in order to extract displacement information. Image-based feature tracking methods that rely on the use of interpolated 2D data are able to provide a robust and precise estimation of surface movements, expressed in terms of displacement fields.

This work presents the comparison of two approaches to compute the displacement fields using two image matching algorithms based on interpolated intensity images: a hierarchical multi-scale image correlation algorithm (e.g. MicMac) and an optical flow algorithm based on the Lucas-Kanade method. Both methods produce an estimation of 2D displacements in image plane, from which 3D displacements can be reconstructed through a back-projection procedure using high resolution DEMs.

The two analysis methods are applied to time series of terrestrial laser scanning point clouds acquired on two slope movements located in the French Alps: the Sanières rockslide (period 2013-2015) in the Ubaye Valley and the Séchilienne rockslide (period 2009-2015) in the Romache Valley. The dense point clouds have been acquired with a terrestrial long-range Optech ILRIS-3D laser scanning device from the same base station.

The computed displacements are compared to GNSS and total station surveys on reference targets located within the landslide bodies and to features tracking on the raw 3D point clouds in order to be validated.

The results indicate that both methods provide an accurate estimation of surface displacement fields and deformation patterns but show limitations such as the inability to accurately track non-rigid deformations, the use of a perspective projection that does not maintain original angles and distances on the interpolated images, and uncertainty on the interpolation accuracy in case of occluded or insufficiently dense ground areas. It indicates that results obtained with 3D point clouds comparison algorithms (C2C, ICP, M3C2) are still useful to add additional information on the displacement fields and help to better understand the long-term dynamics of the landslides.

Information system for subsurface geological data: Find the best solution for the State of Geneva

Maud Brentini[1*], Stéphanie Favre[2*], Gregory Guiliani[3], Anthony Lehmann[3] & Andrea Moscariello[1]

[1] *Department of Earth Sciences, Rue des Maraîchers 13, CH-1205 Geneva; maud.brentini@unige.ch*
[2] *Institute for Environmental Sciences, Bvd Carl Vogt 66, CH-1205 Geneva; stephanie.favre@unige.ch*
[3] *EnviroSPACE Group, University of Geneva, Geneva, Switzerland*

Key words: *geology, subsurface, GIS, resources, management.*

The deep subsurface and its natural resources belong, by law, to the state. A detailed and accurate knowledge of them is therefore central to allowing effective exploitation and management. GEothermie 2020 is a program piloted by the State of Geneva and implemented by the Industrial Services of Geneva (SIG). Aiming to develop the geothermal energy in the Geneva basin, this program offers the opportunity to improve subsurface knowledge by collecting new data, both in two and three-dimensions. As owner of the subsurface, these data need to be gathered, organized and managed by the state. Unfortunately to date, the existing infrastructures are not sufficient to address these needs.

Supported by the State of Geneva, the main objective of this research is to develop a geological database linked to a Geographic Information System (GIS). The whole system has to be able to manage 2D and 3D geological information. Integrated in a multidisciplinary program, our project involves two main research axes:

Firstly, a substantial work on the stratigraphic definition and nomenclature of the Geneva basin has to be carried out. It is necessary to start by crossing and analysing the regional stratigraphy works done through several generations and then connect the different definitions, levels and/or way of interpreting, peculiar to each author. A large work on harmonizing data has to be done in order to correlate all these data. HARMOS program, the new lithostratigraphic framework with standard legends for the Geological Atlas of Switzerland 1:25 000 (MORARD, 2014), will help us in this task. Because we have only little information with boreholes on the deep subsurface, it is important to valorise this wealth of information. In Geneva, we have a great opportunity to understand better the subsurface units by studying them in the surrounding outcrops.

From the geomatics side, the SITG (Système d'information du territoire genevois) is the cantonal platform displaying the geographic information on Geneva. Concerning geological data, only minimum information are currently provided about borehole (depth, first horizons ...), but seismic lines, outcrops, geological sections and deeper geological information are missing (SITG, 2016). Another main challenge relates to the link between 2D and 3D data. The new cantonal platform (ge.ch/sitg/geologie3d) stores and displays 3D models while it allows generating virtual boreholes and cross-sections. However this platform works in isolation from the 2D database system. These considerations imply that the data management system needs to be improved and further expended. Geological information has to be organized in a database system allowing spatial requests and an easier access to the third dimension. Moreover, geological data should also be intersected with information on energy and territorial planning, while ensuring a monitoring of the data through time (4D).

The complete information system will be owned by the State of Geneva and will offer users the capability to find, extract, validate, interpret, process and distribute 2D and 3D geological data. Last but not least, it will provide tools for the State of Geneva to manage its subsurface resources, develop geothermal energy strategies, and care for the environment.

References

MORARD A., 2014. Correlations beyond HARMOS: how, where, why? Swiss Geoscience Meeting 2014. *Platform Geosciences, Swiss Academy of Science,* SCNAT. Conference paper.

SITG, 2016. Système d'Information du Territoire Genevois (SITG), http://ge.ch/sitg/ (Accessed 25.04.2016)

Extended temporal scale of Transantarctic outlet glacier hypsometry using stereographic techniques with historic aerial photographs

Sarah F. Child[1*] & Leigh A. Stearns[1]

[1] *University of Kansas, Dept. of Geology 1475 Jayhawk Blvd. Lawrence, KS 66045, USA; *s021c518@ku.edu*

Key words: *aerial photography, hypsometry, stereographic, Transantarctics, East Antarctica.*

Ice sheet mass balance, the difference between mass gain and loss over a specific period of time, is an indicator of ice sheet stability and contribution to sea level. Over the last 20 years, the mass balance of Greenland and Antarctica has been -213±72 $Gt\ yr^{-1}$, contributing an estimated 11.2±3.8 mm of sea level rise to the oceans (SHEPHERD *et al*., 2012). The latest mass balance estimate for Antarctica is -159±48 $Gt\ yr^{-1}$, with the majority of the mass loss coming from the West Antarctic Ice Sheet (WAIS) (MCMILLIAN *et al*., 2014). Mass balance estimates prior to the 1990s are limited and the earliest records covering the Transantarctic Mountains (TAs), which drain ice from the East Antarctic plateau into the Ross Ice Shelf, are from 1980 and suggest that glaciers were in relative mass balance (RIGNOT *et al*., 2008). Using old aerial photos captured over the largest glaciers flowing through the TAs, we will extend this record back to the 1960s. By utilizing stereographic techniques, the 1960 images spanning five of the TAs' largest outlet glaciers (see Fig. 1) will be converted into digital elevation models (DEM) to compare with present day glacier surface elevations.

To estimate glacier mass balance, we will use geodetic methods of analysing the TAs' outlet glacier hypsometry. Glacier surface elevation changes over extended periods of time are representative of changes in glacier dynamics. The outlet glaciers from the TAs, located in East Antarctica, flow into the Ross Ice Shelf, which is a stable ice shelf that shows no signs of collapsing (VAUGHAN & DOAKE, 1996; ANISIMOV *et al*., 2007). This means that variations in velocity, and thus ice thickness, of TA glaciers will likely be due to changes in subglacial hydrology or thinning at the grounding line. The result of this study will be a temporal extension of mass balance records of the TAs, based on a new 1960 DEM of the largest outlet glaciers.

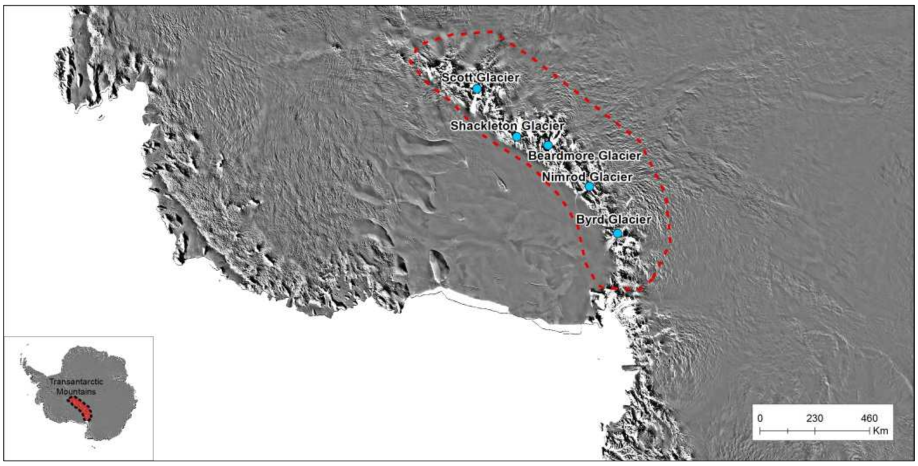


Figure 1: The five glaciers (Scott Glacier; Shackleton Glacier; Beardmore Glacier; Nimrod Glacier; Byrd Glacier) flowing through the Transantarctic Mountains where the mass balance study will take place.

References

ANISIMOV, O.A., VAUGHAN, D.G., CALLAGHAN, T.V., FURGAL, C., MARCHANT, H., PROWSE, T.D., VILHJÁLMSSON, H. & WALSH, J.E., 2007. Polar regions (Arctic and Antarctic). *Climate Change*, 15: 653-685.

MCMILLAN, M., SHEPHERD, A., SUNDAL, A., BRIGGS, K., MUIR, A., RIDOUT, A., HOGG, A. & WINGHAM, D., 2014. Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters 41(11): 3899-3905.

RIGNOT, E., BAMBER, J.L., VAN DEN BROEKE, M.R., DAVIS, C., LI, Y., VAN DE BERG, W.J. & VAN MEIJGAARD, E., 2008. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geoscience*, 1(2): 106-110.

SHEPHERD, A., IVINS, E.R., GERUO, A., BARLETTA, V.R., BENTLEY, M.J., BETTADPUR, S. & BRIGGS, K.H., 2012. A reconciled estimate of ice-sheet mass balance. *Science*, 338(6111): 1183-1189.

VAUGHAN, D. & DOAKE, C., 1996. Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature*, 379(6563): 328-331.

Evaluating roughness scaling properties of natural active fault surfaces by means of photogrammetry

Amerigo Corradetti[1*], Nicola De Paola[2], Ken McCaffrey[2] & Stefano Tavani[1]

[1] *DiSTAR, Università degli Studi di Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy; amerigo.corradetti@unina.it*

[2] *Department of Earth Sciences, Durham University, Durham, UK*

Key words: *photogrammetry, fault roughness, active faults, FFT power spectrum.*

Experimental data relating friction to hold time, slip velocity and displacement are well described by rate and state friction laws. This work shows that the dimensional properties of fault asperities (Dc) control the stability of fault sliding behaviour (DIETERICH, 1979) and thus influences seismic hazard assessment and, to some extent, the development of the spatial architecture of faults.

Fault surface topography shows a self-affine behaviour, which for a Z(X,Y) surface can be described by the scaling transformation Z(X,Y)~X1/Hx~Y1/Hy, where Hx and Hy are the scaling exponents, or Hurst exponents, along the x and y direction respectively. Since these exponents cannot be derived directly (e.g. SAPOZHNIKOV & FOUFOULA-GEORGIOU, 1995), several different methods have been developed in recent years for their estimation. Of these, previous workers have shown that the Fourier power spectrum method has proved to be most reliable (e.g. SAGY *et al*., 2007; CANDELA *et al*., 2009, BISTACCHI *et al*., 2011; RENARD *et al*., 2012). Fault roughness (size of asperities) scales over several length scales with two distinct Hurst exponents in both the slip parallel and perpendicular directions.

To perform FFT analysis, an accurate and detailed topography of faults must be captured. Whilst the capability of standard methods such as lidar, laser profilometers and white light interferometers (e.g. CANDELA *et al*., 2012), is well known, the potential use of photogrammetric methods in fault roughness studies is underexplored.

In this study we used photogrammetry to reproduce the topography of six fault rock samples collected from the main fault surfaces of active normal faults from the Central Apennines that are characterised by a cataclastic matrix and both striated and polished fault surfaces. These rock surfaces were photographed from a 360° range of angles using a tripod to enable higher f/stops to help sharpen the background by increasing the depth of field. Low ISOs were also used to increase exposure time. Extremely dense (average distance of points was about 70μm) point clouds were built in PhotoScan. In Matlab we then performed a FFT analysis on the surfaces along the direction of slip and perpendicular to it using a 1-D FFT approach (e.g. RENARD *et al*., 2012).

Our results (Fig.1) show that the analysed fault surfaces are characterized by an average Hurst exponent of 0.87±0.083 in the direction of slip and 0.95±0.076 perpendicularly to it. These slightly higher values than expected are probably the result of the polished nature of the majority of the analysed fault surfaces. In essence, by means of photogrammetry, we were able to cover part of the resolution attained by lidar, completely overlap that of the laser profilometers and to a small extent part of the scale range attained by white light interferometers.

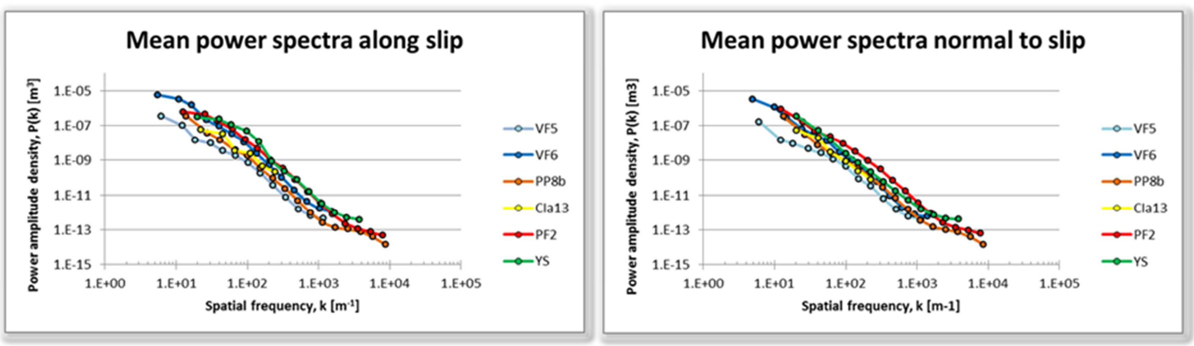


Figure 1: Fourier power spectra of six fault surfaces collected by close-range photogrammetry.

References

BISTACCHI, A., GRIFFITH, W.A., SMITH, S.A.F., DI TORO, G., JONES, R.R. & NIELSEN, S., 2011. Fault roughness at seismogenic depths from lidar and photogrammetric analysis. *Pure and Applied Geophysics*, 168(12): 2345-2363.

CANDELA, T., RENARD, F., BOUCHON, M., BROUSTE, A., MARSAN, D., SCHMITTBUHL, J. & VOISIN, C., 2009. Characterization of fault roughness at various scales: Implications of three-dimensional high resolution topography measurements. *Pure and Applied Geophysics*, 166(10-11): 1817-1851.

CANDELA, T., RENARD, F., KLINGER, Y., MAIR, K., SCHMITTBUHL, J. & BRODSKY, E.E., 2012. Roughness of fault surfaces over nine decades of length scales. *Journal of Geophysical Research*, 117(B8): B08409.

DIETERICH, J.H., 1979. Modeling of tock friction 1. Experimental results and constitutive equations. *Journal of Geophysical Research*, 84(B5): 2161-2168.

RENARD, F., MAIR, K. & GUNDERSEN, O., 2012. Surface roughness evolution on experimentally simulated faults. *Journal of Structural Geology*, 45: 101-112.

SAGY, A., BRODSKY, E.E. & AXEN, G.J., 2007. Evolution of fault-surface roughness with slip. *Geology*, 35(3): 283-286.

SAPOZHNIKOV, V. & FOUFOULA-GEORGIOU, E. 1995., Study of self-similar and self-affine objects using logarithmic correlation integral. *Journal of Physics A: Mathematical and General*, 28(3): 559-571.

Reservoir-scale fracture characterization from an inaccessible carbonate analogue: A UAV photogrammetry application to geology

Amerigo Corradetti[1*], Stefano Tavani[1], Alessandro Iannace[1], Francesco Vinci[1], Carlos Pirmez[2], Stefano Torrieri[2], Maurizio Giorgioni[2], Christoph Strauss[3], Antonio Pignalosa[4] & Stefano Mazzoli[1]

[1] *DiSTAR, Università degli Studi di Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy; amerigo.corradetti@unina.it*
[2] *Shell Italia Exploration and Production, Piazza dell'indipendenza, 11/b 00185 Roma, Italy*
[3] *Shell Development Kuwait*
[4] *Stage S.r.l., Via Forno Vecchio 38, 80034 Marigliano (Na), Italy*

Key words: *structural geology, fracture characterization, digital photogrammetry, UAVs.*

The fast development experienced by both digital cameras and computational speed has open the way to the use of digital photogrammetry for the production of virtual outcrop models in geology. This process was also helped by the versatility of the method that, contrarily to laser scanner, does not require the transport of bulky and heavy devices.

In this contribution we present workflow and results from an inaccessible outcrop, namely the Conocchia cliff (Lattari Mountains, Italy; Fig. 1). The Conocchia cliff is about 250 m wide and 200 m high, with E-W oriented exposure of gently dipping shallow-water carbonates (alternating limestones and dolomites) of Cretaceous age. The use of a UAV (unmanned aerial vehicle) was necessary since the outcrop is exposed toward the gulf of Positano at an altitude over 1100 meters.

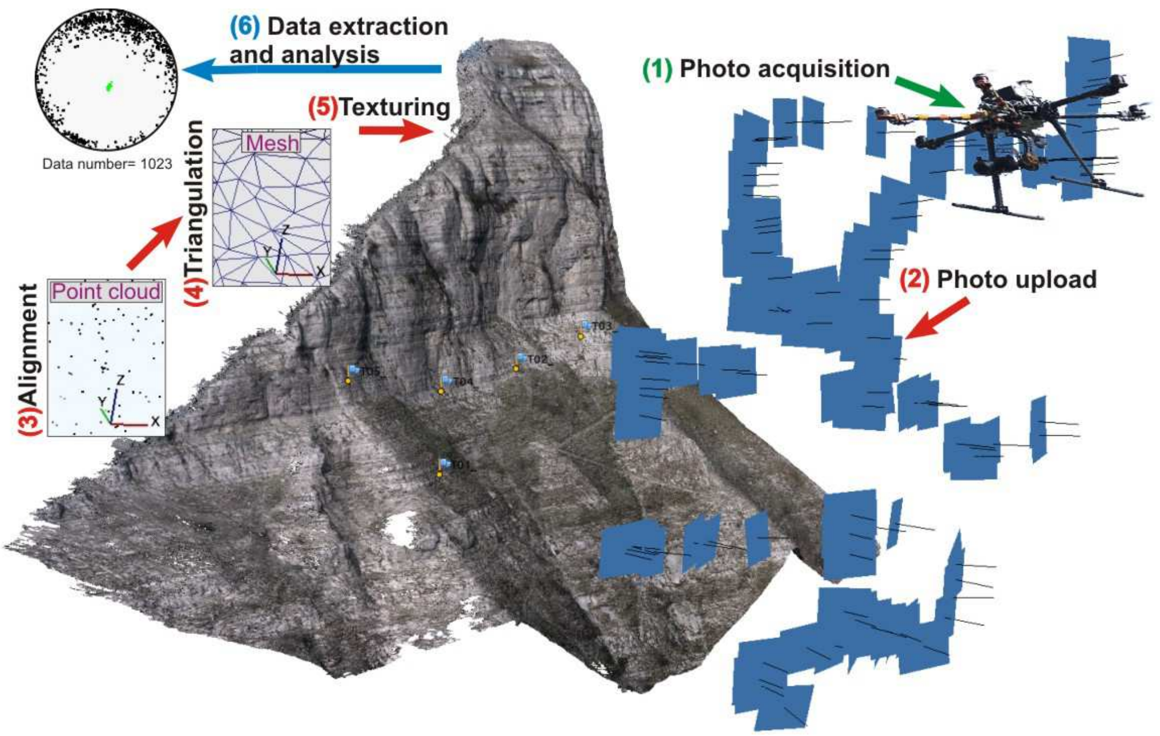


Figure 1: Workflow followed for the 3D fracture characterization of an inaccessible carbonate analogue. Photographs were acquired by means of a drone (1) and later imported in PhotoScan (2), where, through the processes of photo-alignment (3), geometry-building (4) and texturing (5), a 3D photorealistic model was generated. Later, by means of the OpenPlot free software, structural data were extracted from the model (6).

The UAV was equipped with a mirrorless Sony Nex-7 photo-camera that acquired 105 photographs (24.3 Mpixels each) of the cliff from different points of view and at different angles with respect to the outcrop. A total station was used to measure the accurate position of five points within the cliff (blue flags in Fig. 1) to ensure the post processing scaling and re-orientation of the virtual outcrop model (VOM).

Photographs were imported into Agisoft PhotoScan where, following the well-established processing workflow, a trustworthy 3D VOM of the cliff was generated. Later, the model was imported into the OpenPlot free software, where bedding surfaces and fractures were digitized clicking point by point along the intersection between the topography and each geological surface. The result was the digitization of 1003 fractures larger than few meters and up to some tens of meters (Fig. 2). These fractures belong to three sets at high angle to bedding, grouped according to orientation as: ENE-WSW (set 1), ESE-WNW (set 2) and NW-SE (set 3). Each set was projected onto a panel which is perpendicular to the direction of intersection with bedding (Fig. 2). Discarding set 1 that was almost parallel to the cliff (and hence affected by an orientation bias), the obtained panels favoured the geospatial fracture analysis of the outcrop yielding quantitative datasets describing size and vertical continuity of those reservoir-scale through-going fractures (Fig. 2). In addition, through a complementary stratigraphic study of the succession exposed at the Conocchia cliff, we were able to appreciate that major bed-perpendicular through-going fractures arrest against packages made of thinly stratified layers of dolomites, while they pass across medium to thick beds (bed thickness > 30 cm). In essence, through-going fractures arrest on weak levels, consisting of thinly-bedded layers interposed between packages made of several thick beds, exactly like bed-confined fractures arrest on less competent interlayers.

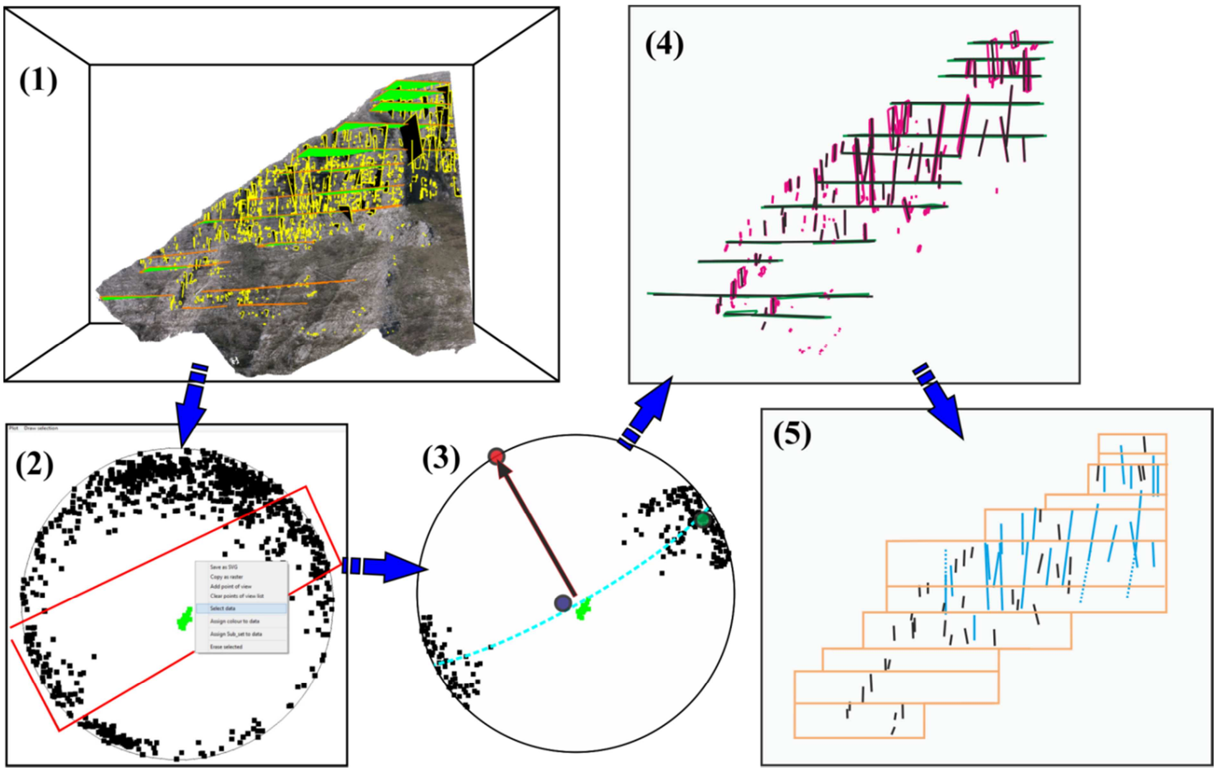


Figure 2: Data analysis workflow. (1) Attitude data extracted from the VOM were analysed by cluster orientation. (2) Each cluster is manually selected and (3) a tensor analysis performed in order to reveal the statistical direction of intersection between bedding and the cluster. (4) The direction of intersection is used to project the selected features toward a perpendicular panel. (5) The mechanical stratigraphy of the outcrop with respect to through-going fractures is revealed.

Distributed processing of Dutch AHN laser altimetry changes

Máté Cserép[1*] & Roderik Lindenbergh[2]

[1] Department of Cartography & Geoinformatics, Eötvös Loránd University, Budapest, Hungary, mcserep@inf.elte.hu

[2] Department of Geoscience & Remote Sensing, Delft University of Technology, Delft, Netherlands

Key words: *lidar, change detection, big data, cloud computing.*

Detection of changes in human-made structures in urban areas – caused by either planned or natural reasons – can provide useful information for government agencies on several fields ranging from land usage through urban planning and civil engineering to disaster management.

The evolution of remote sensing and light detection and ranging (lidar) in the last few decades offered a technology capable of rapid high resolution capture of surface altimetry data through airborne laser scanning. The increasing quantity and improving quality of measurements raised new challenges regarding the computation and memory efficient analysis of these massive datasets. Distributed and cloud computing systems have been around for years, proven to be notably useful in static or rarely altering big data processing, applied in numerous fields including Geographic Information Systems (GIS). Recent research addresses the importance of the management of rapidly growing spatial datasets (YANG & HUANG, 2013). Distributed lidar processing toward digital elevation models also received significant attention from the scientific community (HEGEMAN *et al.*, 2014; JIAN *et al.*, 2015). However, analysis on higher abstraction level spatial features is still an unsolved challenge in multiple aspects.

Our paper proposes a methodology to automatically evaluate altimetry change detection on massive datasets in a cloud computing environment like Hadoop or Spark. As a demonstration, our building construction, demolishing and change detection algorithm was evaluated on measurements from the nation-wide AHN (Actueel Hoogtebestand Nederland) altimetry archive of the Netherlands, comparing the AHN-2 dataset and the available subset of the ongoing AHN-3 data acquisition. To retrieve elevation changes, digital surface models (DSM) generated from the point clouds were compared at a 0.5 m resolution. The choice of using a DSM instead of the raw point clouds enabled faster and more efficient evaluation while maintaining an adequate resolution for change detection in larger artificial objects.

Figure 1: Sample urban area in Delft with satellite image (left) and detection of changed buildings (right).

The currently considered input dataset contains 426 tile pairs, requiring an accumulated storage space of 0.5 TB, The final dataset will occupy near 1.5 TB once the AHN-3 measurements will be completed. To enable the efficient handling of data of this magnitude, tile pairs were compared and processed in a parallel manner with the utilization of distributed computing. The implementation was carried out in C++ based on the open source GDAL/OGR geospatial and geoprocessing software library. First, the changeset between tile pairs was calculated, discarding alterations under the accuracy threshold corresponding to the quality specifications of the AHN measurements (VAN DER ZON, 2013). Buildings and other artificial changes were detected by examining the noise and the planar features of the DSM grid points. Finally small, insignificant cluster of changes (e.g. construction of a chimney) were removed from the results, as our research aimed to locate modifications on a larger scale.

References

HEGEMAN, J. W., SARDESHMUKH, V. B., SUGUMARAN, R. & ARMSTRONG, M. P., 2014. Distributed LiDAR data processing in a high-memory cloud-computing environment. *Annals of GIS*, 20(4): 255-264.

JIAN, X., XIAO, X., CHENGFANG, H., ZHIZHONG, Z., ZHAOHUI, W. & DENGZHONG, Z., 2015. A Hadoop-based algorithm of generating DEM grid from point cloud data. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(7): 1209-1214.

VAN DER ZON, N., 2013. Kwaliteitsdocument AHN2, http://ahn.nl, version 1.3.

YANG, C. & HUANG, Q., 2013. *Spatial Cloud Computing: A Practical Approach*. CRC Press, Boca Raton, FL, USA.

Seismic imaging of deeply emplaced mafic sill complexes

Christian Haug Eide[1,*], Nick Schofield[5], Isabelle Lecomte[1,3,4], Simon J. Buckley[2,1] & John Howell[5]

[1] *Department of Earth Science, University of Bergen, 5020 Bergen, Norway; Christian.eide@uib.no*
[2] *Uni Research CIPR, P.O. Box 7810, N-5020 Bergen, Norway*
[3] *NORSAR, P.O. Box 53, N-2027 Kjeller, Norway*
[4] *University of Oslo, Deptartment of Geosciences, P.O. Box 1047, Blindern, 0316 Oslo, Norway*
[5] *School of Geosciences, Meston Building, University of Aberdeen, Aberdeen, AB24 3UE, UK*

Key words: *lidar, sedimentology, petroleum geology, volcanology, seismic modelling.*

The application of 3D seismic data has led to a revolution in the understanding of architecture of mafic sill complexes, and their influence on basin history, fluid flow, and implications for magma transport in the crust, feeding relationships to volcanoes and influence on hydrocarbon systems. However, considerable uncertainty exists on how the seismic observations relate to actual geometries and architecture of sill complexes, as the seismic method has considerable limitations, mainly: (1) decrease of seismic quality and resolution with depth due to absorption of high frequencies, seismic energy and downward increase in seismic velocity; (2) overburden effects, where the seismic signal is affected by complex overburden which can be a considerable problem in basins with igneous rocks; and (3) the inability of the reflection seismic method to image steeply dipping and vertical interfaces.

In order to assess the seismic imaging of actual sill complexes, synthetic seismograms simulating zero-phase, depth-migrated seismic data are generated from outcrop data constrained by lidar and abundant field data. The outcrop is a 22 x 0.25 km, world-class exposure of Jurassic clastic sedimentary rocks intruded at c. 3 km depth by Eocene dolerite dykes from Jameson Land, East Greenland. This dataset is compared to different subsurface 3D-seismic dataset with and without well control.

The study shows that significant overestimation of sill thickness and volume may occur using seismic data, and that unimaged oblique dykes and vertical sills may occur. Furthermore, this study highlights the variability and complexity of seismic imaging of sill intrusions, and show that seismic modelling of acquisition and processing parameters to understand which components may be imaged and which may not.

Acknowledgements: We thank the Research Council of Norway and sponsors for funding through the FORCE SAFARI project and Trias North (project 234152). This funding has been used for funding for fieldwork, data acquisition, interpretation and method development.

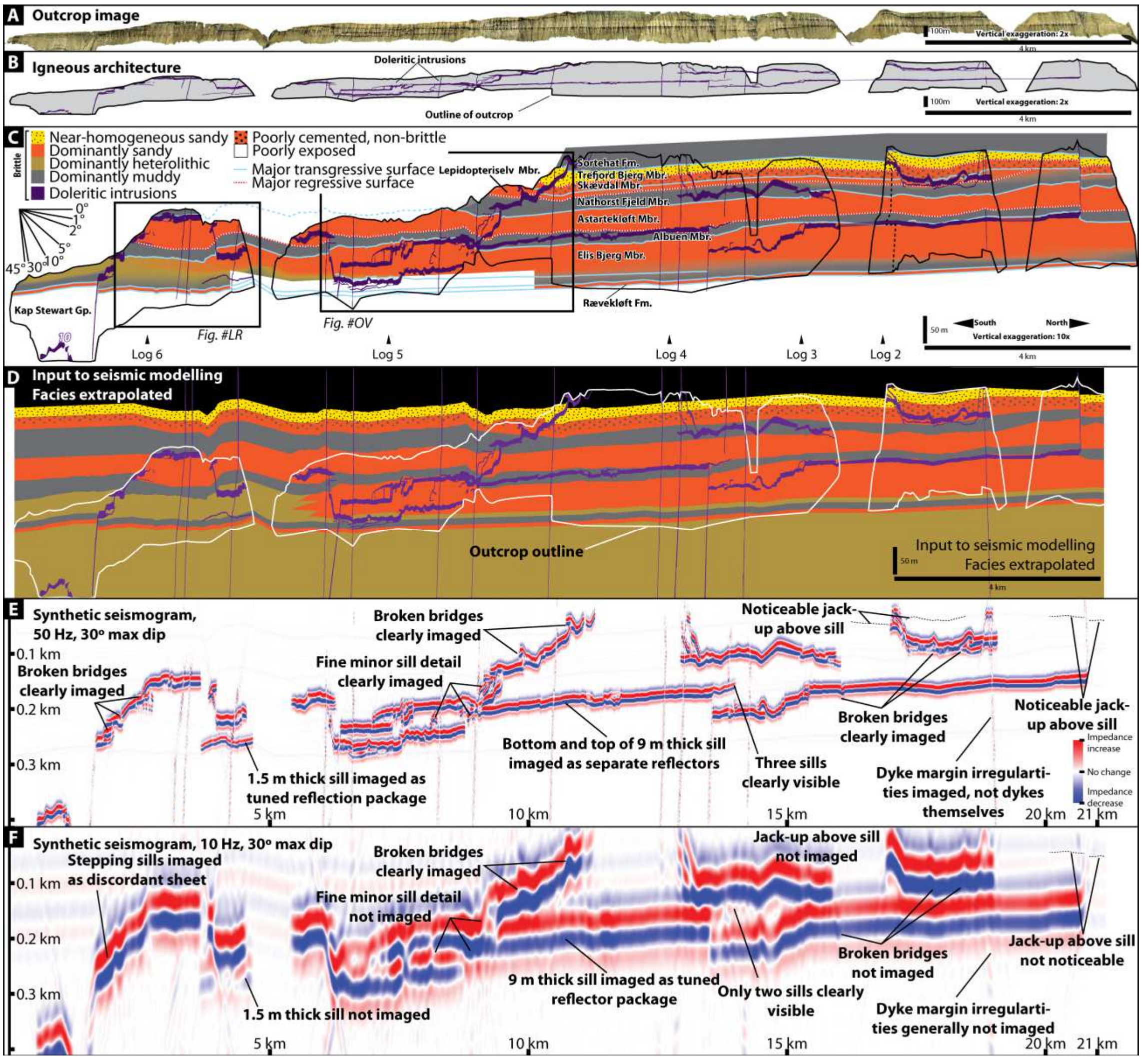


Figure 1: (A) Lidar model of cliff face in eastern Greenland showing sand and mudstone intruded by a volcanic feeder system (black); (B-C) Geological interpretation; (D) Input to seismic modelling; (E-F) Synthetic seismograms at 50 and 10 Hz, with imaging issues overlain.

Clay mineral mapping in underground potash mines using corrected intensity lidar data at 905 nm

Angus F.C. Errington[1, 2,*], Brian L. F. Daku[1] & Arnfinn F. Prugger[2]

[1] *University of Saskatchewan, Department of Electrical and Computer Engineering, 57Campus Dr., Saskatoon, SK, S7N 5A9, Canada*

[2] *Potash Corporation of Saskatchewan Inc., 122 1st Avenue S, Suite 500 Saskatoon, SK, S7K 7G3, Canada*

Key words: *lidar, TLS, measurement, geoscience, reflectance.*

This study presents an initial investigation into using estimated reflectance, derived from raw terrestrial laser scanner intensity data, to model clay content within a potash mine. The mines of interest are located in the Prairie Evaporite Formation about 1 kilometre underground in the province of Saskatchewan, Canada. It is shown that with an appropriate reflectance estimation process, as presented in (ERRINGTON *et al*. 2015), it is possible to produce consistent reflectance estimates over different distances and angles for a sylvinite deposit containing interbedded clays. Estimating the reflectance assures that measurements are repeatable with separate instruments and at different distances and angles. The main contributions of this paper are:

(i) An application of intensity-derived reflectance to clay mapping within a potash seam;

(ii) Verification that this model of "diffuse reflectance" can be applied to real non-lambertian surfaces;

(iii) Comparison between modelled reflectance to assay results as an indicator of clay/mineral content.

The estimated reflectance values for different distinct regions of a typical mine wall, shown in Fig. 1, were compared with assay results. The distinct regions were segmented based on geologic lithography as well as intensity uniformity. If a linear relationship is assumed then R^2 values ranging from 0.51 to 0.92 were observed. The higher R^2 values (above 0.86) were for SiO_2, MgO, Al_2O_3, CaO, TiO_2 and Fe_2O_3, which are indicative of increased clay content. This shows that there exists a possibility of using the estimated reflectance from a Faro Focus3D 120 (operating at 905 nm) to map clay mineral content in underground potash mines. More research needs to be conducted to determine if the relationships observed in this study are applicable on a larger regional scale.

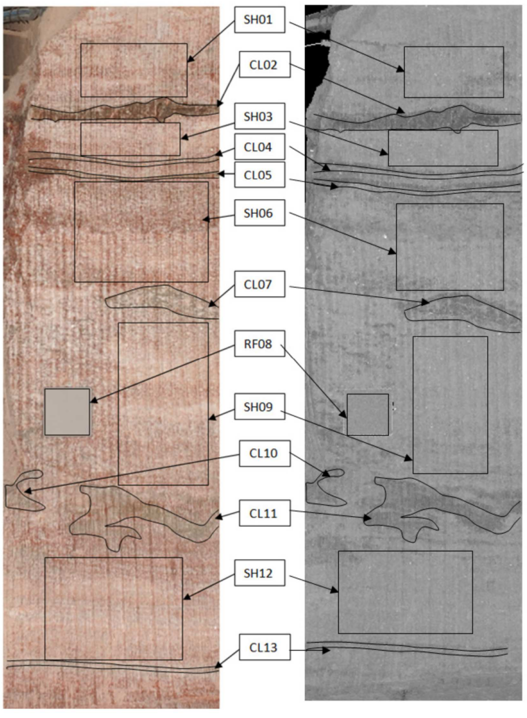
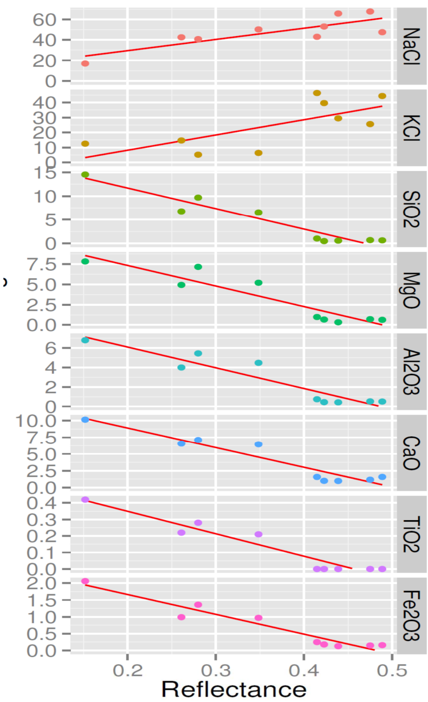


Figure 1: Two point clouds of the same region. The one on the left is coloured with camera data and the one on the right is coloured with received intensity data.



e estimated reflectance obtained
-e linear models fit to the data.

and PRUGGER, A.F., 2015

Figure 2: The assay results compared to the estimated reflectance obtained from the Faro Focus3D 120 of the various regions shown in Fig. 1. The red lines are linear models fit to the data.

Reference

ERRINGTON, A.F.C., DAKU, B.L.F. & PRUGGER, A.F., 2015. Reflectance modelling using terrestrial lidar intensity data. In Proceedings of the 2015 *IEEE International Conference on Imaging Systems and Techniques (IST)*, September, Macau, China.

User-guided structural interpretation toolbox for digital outcrop models

Marie Etchebes[1], Aicha Bounaim[1], Trond Brenna[1] & Paul Tapponnier[2]

[1] *Stavanger Schlumberger Research Centre, Norway*
[2] *Earth Observatory of Singapore, Singapore*

Key words: *lidar, modelling, automation.*

To characterize structurally-complex reservoirs, it is essential to understand the impact of fault and fracture networks on cap rock integrity and fluid flow behaviour. In particular, fault and fracture kinematics, permeability characteristics, sealing capacity and scaling properties need to be constrained. Faults and fracture swarms can be detected on seismic data while single fractures are in general below seismic resolution and only visible in well data such as borehole image logs and cores. To obtain the extra information needed to build and populate reservoir models away from wells, outcrop analogues are often used to bridge the gap between seismic resolution and well logs. They especially provide insights into the characteristics of natural small-scale fracture patterns, as well as their relationship with seismic-scale faults.

Nowadays, digital outcrop models (DOMs), or digital elevation models (DEMs) are built by combining laser scanning technology (lidar) with digital photogrammetry and remote sensing. While the acquisition and processing of digital models are affordable, fast and mostly automatic, their interpretation remains time-consuming as it is mostly done manually. Along with these technologies comes an increase in data volume and complexity promoting new approaches for user-guided automated interpretation tools.

This study aims at automatically extracting and characterizing multi-scale geological discontinuities and associated sedimentary deformation directly from highly dense lidar-derived DOMs combined with DEMs. For this purpose, an automated processing workflow is proposed. The approach starts by removing unwanted features like vegetation from the raw dataset. This step is followed by the generation of an optimal texturized triangulated mesh where the resolution depends on the degree of details to be kept. Simultaneously, an analysis is performed on the lidar point cloud to extract most of the 3D geometric information such as dip, azimuth, planarity, and dilation angle. The analysis is then supplemented by an interactive filtering and classification allowing more interaction of the interpreter on a common 3D platform. The final results include, in particular, quantitative properties for heterogeneities like orientation, dip, length, and density.

To assess the proposed methodology, a feasibility test has been conducted on the combination of ground-based lidar data, digital photos and satellite imagery from the Fuyun fault complex, China.

Rockfall source area detection and characterisation from terrestrial laser scanner (TLS) data

Xabier Blanch-Górriz[1], David García-Sellés[1*], Marta Guinau[1] & Manuel J. Royán[1]

[1] RISKNAT Research Group, GEOMODELS Research Institute, Dpt. Dinàmica de la Terra i de l'Oceà Facultat de Geologia, Universitat de Barcelona, c/ Martí i Franquès s/n, 08028 Barcelona, Spain. dgarcia@ub.edu

Key words: *lidar, rockfalls, rock structure, cultural heritage.*

The emphasis of this research is on characterizing rockfall source areas by analysing 3D discontinuity sets identified from TLS data, in order to describe the mechanisms and possible features and volumes of potential rockfalls. This work is developed in the Montserrat Massif located about 50 Km north-west of Barcelona (Spain). The study site includes rock faces affecting one of the most exposed access roads, characterised by an area of 2 ha and a maximum height of 90 m.

A first approach on the detection and characterization of the rockfall source zones is developed by visual inspection at the field. Subsequently, the discontinuity sets are analysed from TLS point clouds, by using the SEFL (Surface Extraction from Lidar) application developed by García-Sellés *et al*. (2011). Briefly the SEFL application is based on the planar regression of the point cloud that allowed the computation of the dip and dip direction of the different continuous surfaces. The computation of a series of quality parameters of the resulted data and a clustering process allows the individual extraction of discontinuity sets (Fig. 1 and 2) and the obtaining of a morphometric model of the discontinuities. Afterward the mean surface length and the mean spacing are calculated for each discontinuity set. Field measurements and observations are used to validate the discontinuity sets characteristics defined from TLS data, since TLS point cloud is normally affected by occlusion and certain biases.

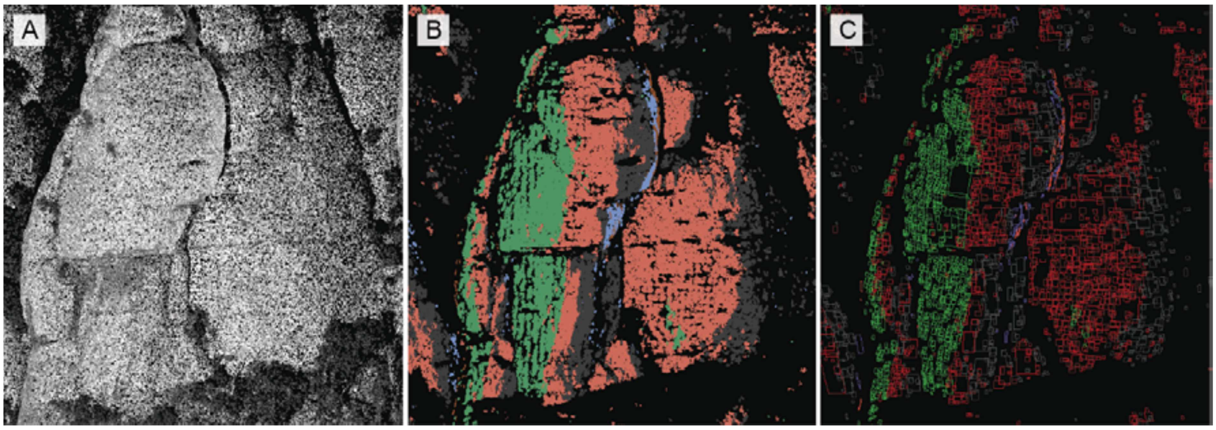


Figure 1: Results from the SEFL application to obtain the discontinuity sets affecting the rock cliff. A: TLS point cloud. B: Points showed in different colours depending on which discontinuity set they belong. C: Morphometric model.

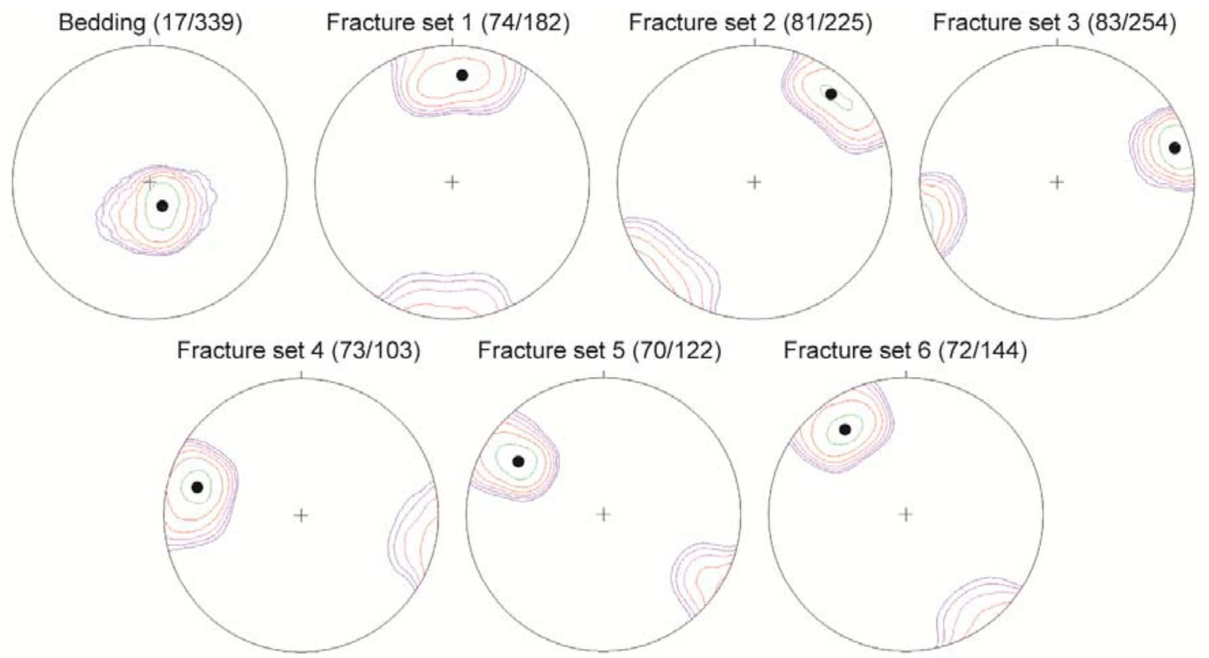


Figure 2: Pole density stereographic representations and mean dip and dip direction for each discontinuity set and bedding.

The results are compared with the ones obtained in further works developed in other sectors of the Montserrat Mountain, in order to detect possible differences in the morphometry of the rockfalls. The characterization of the source zones attained provides compulsory information for the design and implementation of protective measures to reduce the rockfall risk in the study area.

Acknowledgements: The work has been partially supported by the Spanish Ministry of Science and Innovation project CHARMA (CGL2013-40828-R), the project "LiDAR applications on rockfall study in Montserrat Mountain (year 2015)" of the Institut Cartographic i Geològic de Catalunya (ICGC), the research group RISKNAT (2009SGR-520) and the GEOMODELS Research Institute.

Reference

GARCÍA-SELLÉS, D., FALIVENE, O., ARBUÉS, P., GRATACÓS, O., TAVANI, S. & MUÑOZ, J.A., 2011. Supervised identification and reconstruction of near-planar geological surfaces from terrestrial laser scanning. *Computers & Geosciences*, 37: 1584-1594.

Opportunistic survey of glaciers using low-cost equipment

Luc Girod[1*], Christopher Nuth[1] & Jack Kohler[2]

[1] Department of Geosciences, University of Oslo, Postboks 1047 Blindern, 0316 Oslo, Norway
[2] Norwegian Polar Institut, Framsenteret, Hjalmar Johansens gate 14, 9296 Tromsø, Norway

Key words: *photogrammetry, glaciers, low-cost.*

The capability of structure from motion (SfM) photogrammetric techniques to survey geomorphological objects – such as glaciers, moraines or landslides – at very high spatial and temporal resolutions is a promising tool for better quantification and understanding of the associated processes. Modern software and computing power allow us to produce accurate datasets from low-cost surveys, which enhance our observational capability to a wider range of processes. We present a method to take advantage of light transport flights to collect imagery for geomorphological analysis.

Our method exploits the malleability of SfM photogrammetry compared to classical photogrammetry on flight path requirement and aircraft stability. In this study, we test and validate an approach to attach simple cameras and hiking GNSS receivers to aircrafts conducting other missions in order to collect data when the flight path is over an area of interest. A key novelty in our method is the proposed way to link the GNSS information to the images without a physical or electronic link. The absence of associated costs allows for failed trials and the collection of surplus of images that could also be used for other projects if properly archived.

As a proof of concept, we conducted two test surveys in September 2014 and 2015 over Midtre Lovénbreen glacier and its fore field. Midtre Lovénbreen is a ~5 km^2 glacier situated in a north-facing catchment on Brøggerhalvøya, NW Svalbard, and has one of the longest continuous mass balance records of the Arctic. We used GoPro Hero 3+ BE taking one picture per second and a GARMIN GPSmap 60CSx attached to the underbelly of a helicopter (see Fig. 1). The flights we took advantage of were planned for ice stake surveys on the neighbouring Kronenbreen.

Figure 1: Equipment used for our surveys (GARMIN GPSmap 60CSx, Eurocopter AS350 and GoPro Hero 3+ BE).

A DEM and an ortho-image are generated at 1m resolution from about 400 images collected using the free open source photogrammetric suite MicMac (PIERROT-DESEILLIGNY *et al.*, 2016). The comparison with a professional photogrammetric 2010 DEM (1 m resolution) shows an absolute error in the direct registration of about 3m in Easting, Northing and elevation. Co-registration of the DEMs using stable ground (with the method from NUTH & KÄÄB, 2011) leads to an RMS in the elevation of ±3.5 m.

DEM differencing shows glacier retreat (~12 m.y1) as well as dynamics in the western moraine (see Fig. 2) in both comparisons with the 2010 DEM and between our two surveys (2014 and 2015).

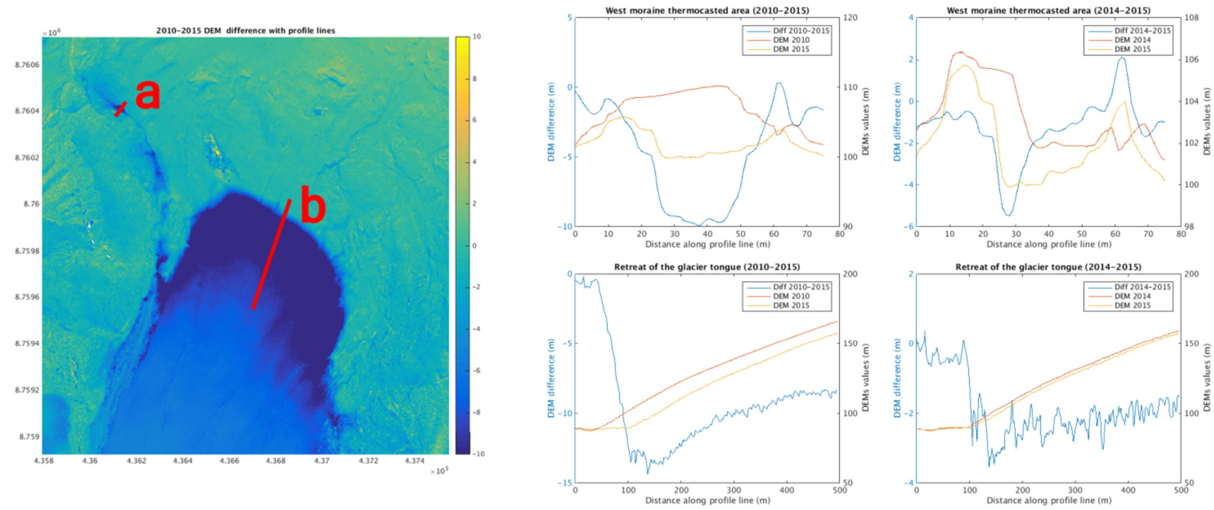


Figure 2: Left: DEM difference at the tongue of the glacier (2010 vs 2015) and positions of the profile lines (red). Right: profile lines on DEMs and DEM differences (Top: A, Bottom: B).

Acknowledgements: The study was funded by the European Research Council under the European Union's Seventh Framework Program (FP/2007-2013)/ERC grant agreement no.320816 and the ESA project Glaciers_cci (4000109873/14/I-NB). The flights were operated for the Norwegian Polar Institute by Jack Kohler.

References

PIERROT-DESEILLIGNY, M., JOUIN, D., BELVAUX, J.,MAILLET, G., GIROD, L., RUPNIK, E.,MULLER, J. & DAAKIR, M., 2016. MicMac, Apero, Pastis and Other Beverages in a Nutshell! http://logiciels.ign.fr/?-Micmac,3-. ENSG, IGN, Champs-Sur-Marne, France.

NUTH, C. & KÄÄB, A., 2011. Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change, *Cryosphere*, 5, 271–290.

Generation of 3D models using panoramic camera for indoor and outdoor scenarios: System calibration, test and first results

Nives Grasso[1*], Andrea Lingua[1], Marco Piras[1]

[1] *Politecnico di Torino, DIATI, Department of Environment, Land and Infrastructure Engineering, Torino, Italy; name.surname@polito.it*

Key words: *panoramic camera, Spherical images, MMS, 3D models, sensors integration.*

In recent years there has been a considerable increase in the use of spherical images (Fig. 1) for three-dimensional documentation of urban environments, archaeological heritage (D'ANNIBALE, 2011), indoor environments (KWIATEK *et al*., 2014) and combined applications integrating laser scanners (KANG *et al*., 2009). Nowadays there are many software packages dedicated to the processing of images through structure from motion (SfM) and computer vision (CV) algorithms, but only some of them were adapted to spherical images. Knowing the internal calibration parameters of the camera, suitable software is able to quickly align the spherical images and georeference the model according to control points.

Figure 1: Panoramic image created by stitching algorithms on four plane images, acquired during the tests with the camera NCTech iSTAR.

Several tests were conducted in hallways of the Politecnico di Torino through the use of the NCTech iSTAR Fusion panoramic camera, composed of four fisheye lenses.

This camera was mounted on a cargo bike Panda Bike Minivan (Fig. 2), connected with a computer and an Inertial Measurement Unit (IMU). This type of vehicle allows capture data to be captured rather quickly, move along the aisles with some ease, ensuring the mechanical stability of the sensors. As well known (MCGLONE *et al*., 2004), each optical device has radial and tangential distortion due to optical lens, which lead to an image that is not a central projection. In order to use these images for photogrammetry, the research will focus on the estimation of the radial and tangential distortion parameters of the camera lenses and on the analysis of image quality.

A comparison between models obtained varying some acquisitions parameters, allowed to evaluate the accuracy of the produced point clouds. The reference model for the analysis on the achieved accuracy is a lidar point cloud acquired with the Trimble Indoor Mapping Solution (TIMMS), with which the three-dimensional products of the spherical images will be compared.

Figure 2: Panda bike minivan, on which the image acquisition system was installed.

Finally, further tests were performed in order to assess the quality of the 3D models obtained by the integration of the spherical images with images acquired by the action-cam Garmin Virb Elite, also mounted on the MMS.

This article aims to analyse the potential of this approach for evaluating the structural safety inside school buildings. These systems, in fact, provide a fast data acquisition if mounted on Mobile Mapping Systems (MMS) and, eventually, could be used in areas not accessible using an unmanned ground vehicle (UGV) (KRUIJFF *et al.*, 2012).

References

D'ANNIBALE, E., 2011. Image based modeling from spherical photogrammetry and structure for motion. The case of the treasury, Nabatean architecture in Petra. *Geoinformatics FCE CTU*, 6: 62-73.

KANG, Z., LI, J., ZHANG, L., ZHAO, Q. & ZLATANOVA, S., 2009. Automatic registration of terrestrial laser scanning point clouds using panoramic reflectance images. *Sensors*, 9(4): 2621-2646.

KRUIJFF, G.J.M., TRETYAKOV, V., LINDER, T., PIRRI, F., GIANNI, M., PAPADAKIS, P. & PRIORI, F., 2012. Rescue robots at earthquake-hit Mirandola, Italy: a field report. In: *Safety, Security, and Rescue Robotics (SSRR)*, 2012 IEEE International Symposium on (pp. 1-8). IEEE.

KWIATEK, K. & TOKARCZYK, R., 2014. Photogrammetric applications of immersive video cameras. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5): 211.

MCGLONE, J.C., MIKHAIL, E. & BETHEL, J., 2004. *Manual of Photogrammetry, 5th Edition*, American Society for Photogrammetry and Remote Sensing, 5th edition, Bethesda, MD.

Multi-temporal DEM extraction using archival aerial photos: Case study of the Czarny Dunajec River, Polish Carpathians.

Maciej Hajdukiewicz

Faculty of Environmental, Geomatic and Energy Engineering, Kielce University of Technology, Poland, mhajdukiewicz@tu.kielce.pl

Key words: *photogrammetry, digital elevation model.*

The main aim of the study was to evaluate usefulness of the photogrammetric DEM extraction method for the survey of river channel changes based on a case study of the Czarny Dunajec River. The river channel was an object of field research conducted in the years 2000-2013, which documented landforms resulting from the recent activity of the river. Thus the verification of the modelling is possible through the comparison of DEM and field measurements. An accuracy analysis of the DEM obtained from archival aerial photos allows to improve technology of elaboration of this material and DEM extraction, that can be applied to other areas with similar dynamics of geomorphological processes. Archival aerial photos of the study area were gained for the following time intervals: 1954-56, 1963-65, 1977, 1983, 1994, and 2012. Additional materials comprised orthophotos and DEMs from 2009, and a DEM from 2012. Three test areas were selected for a comparison of the DEM extracted from the stereopairs of the sequential aerial photos. Then the changes of relief could be surveyed as differential models using map algebra algorithm. The key issue was to evaluate the accuracy of each DEM and to determine the factors that affect it in order to improve the photogrammetric survey. A set of control points was surveyed for each photogrammetric project, established for each test area and time epoch, referring to the exact 2012 DEM, acquired using lidar, and GPS control points surveyed by GNSS in 2013. The accuracy of the extracted DEMs varies due to different accuracy of aerotriangulation, expressed by RMS error after bundle adjustment process. These errors did not exceed 0.25 m for any time epoch. Generally, a strong relationship between the value of the observed error and the age of aerial photos was found, caused by several factors such as the radiometric quality of the photos, geometric distortion of the photo material (due to improper storage conditions), and uncertainty of the GCP locations. The mean error of the ground observations referenced to the lidar, or GPS elevation data is on a relatively high level of 0.3-0.4 m, with local maximum values over 1m, probably caused by insufficient radiometric and geometric quality of the photos. This means that the techniques of the photo distortion correction and radiometric quality enhancement are the crucial issues for the improvement of the DEM extracted from the archival aerial photos.

Acknowledgements: This study was performed within the scope of the Research Project DEC-2013/09/B/ST10/00056 financed by the National Science Centre of Poland.

3D displacement retrieval on a scaled model of mountain slope by virtual multi-view photogrammetry

Haixing He[1*], Flavien Vernier[1], Estelle Ployon[2] & Thierry Villemin[2]

[1] LISTIC Laboratory, University of Savoie, Annecy-Le-Vieux, France; haixing.he@univ-savoie.fr
[2] EDYTEM Laboratory, University of Savoie, Annecy-Le-Vieux, France

Key words: *photogrammetry, change detection, laboratory measurement, digital elevation model.*

Displacement surveys on mountain slopes are important for forecasting and preventing natural disasters such as landslides. Recent research in photogrammetry allows monitoring movements by comparing multi-temporal DEMs, measuring 2D displacements from multi-temporal orthophotos or measuring points' coordinates on moving area by GPS. In spite of the variety of these methods, it is still difficult to investigate dense 3D displacements because of the complexity of slope movement. In this article, we propose a new method for dense 3D displacement retrieval by using multi-view and virtual photogrammetry techniques. The final result is a map of mobile areas, in which 3D displacement vectors could be drawn on each pixel. This map helps to better understand the slope movement especially in areas where displacements are not homogenous.

Limited by the speed of displacement on mountain slope, we established an experiment for simulating the landslide on a scaled model. This model allows us to control as many influenced factors as possible during data acquisition, so that we can easily focus on the movement. A pile of sand covered by cobbles and rocks is used for representing a mountain slope. They are loaded in a dump truck. When the hopper is raised from one inclination to another, cobbles and rocks creep down until stable. These displacements, representing mountain slope surface displacements, are what we observe. In our experiment, the hopper has been raised at one higher position, with sand and rocks sliding down slowly and restabilising in another state. For each state, a set of images has been taken by a camera Nikon D800. The camera was carried manually and two lenses (35 mm and 85 mm) were used for acquisition: the 35 mm is for producing global images while the 85mm is for shooting detailed images.

Our 3D displacement retrieval method consists of three main parts: reconstruction of a 3D point cloud, generation of multiple 2D displacements maps and fusion of 3D displacement maps. We use PhotoScan for reconstructing point clouds from images of each state. The point cloud of the first state is referenced by targets installed on the truck. These targets were measured by a total station. The second point cloud is referenced by using coordinates of the first state's targets. In this way, the hopper in two point clouds overlaps. Once two point clouds are aligned, a virtual camera is created for taking pictures at the top of each point cloud. The virtual acquisition process can be seen as a projection of 3D points on an image plane; it generates one image of each point cloud. By calculating correlation of these two virtual images, a 2D displacement map is produced. Since intrinsic and extrinsic parameters of virtual camera are modifiable, we placed it at 5 different positions for taking more pictures of two point clouds. Each pair of virtual images produces a 2D displacements map. As a 2D displacement can be seen as a projection of 3D displacement, a 3D displacements map can be therefore fused from three or more 2D displacement maps by an inversion technique (YAN, 2011).

Fig. 1 is a 3D displacement map of sand and rocks. In this map, 3D displacement has been calculated for each pixel. In the mobile area, arrows point to the direction of displacement on the image plane, the length of arrows represents amplitude of displacement on image plan and the colour of arrows stands for the vertical displacement amplitude. In order to identify moving areas, we calculated distance of two point clouds in CloudCompare. We found distance in most of area is less than 2 mm except two places indicated in Fig. 1. As can be seen from the 3D displacement map, these two places are where large rocks slip down so that colours of arrows in these areas are brighter.

In conclusion, most of arrows correspond to direction and amplitude of movement. In addition, the minimum displacement our method has detected in this experiment is about 1.2 mm. Arrows pointing upwards or in area where there is no sand are errors coming from correlation, lighting changes and displacement of small gravel.

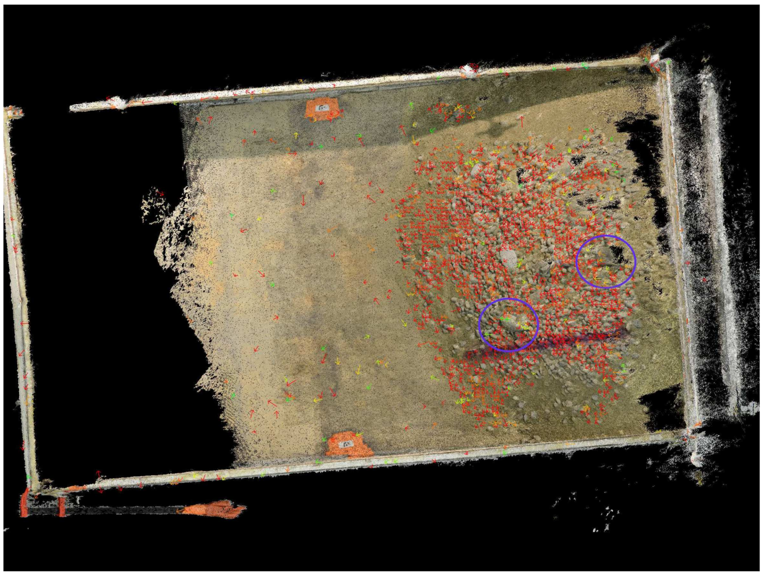


Figure 1: 3D displacement map.

Reference

YAN Y., 2011. Fusion de mesures de dplacement issues d'imagerie SAR: application aux modlisations sismo-volcaniques. PhD thesis, University of Savoie.

High-resolution model of the Bilila-Mtakataka Fault, Malawi using Pleiades stereo-imagery and UAV-based structure from motion

M. Hodge[1*], A. Fagereng[1], J. Biggs[2] & H. Mdala[3]

[1] *School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK; hodgems@cardiff.ac.uk*
[2] *School of Earth Sciences, University of Bristol, Bristol, UK*
[3] *Geological Survey Department, Mzuzu Regional Office, Malawi*

Key words: *Pleiades, photogrammetry, earthquake, UAV, faults.*

Over the past few decades, several theories on how large faults develop and grow have been proposed. The 'isolated fault' theory states that smaller individual faults interact with one another, before forming a geometrical link. Hard-linked fault 'segments' may then either rupture individually or continuously during earthquakes, leading to different magnitudes and seismic hazard. SRTM imagery is commonly used for fault displacement analysis on large, mature faults, i.e. those that have accumulated large amounts of displacement (102 to 103 m). Studying individual fault segments or immature, large faults requires high resolution satellite imagery as cumulative and earthquake incremental displacements may be less than the SRTM resolution (30 m). For this, satellite stereo-imagery such as Pleiades and/or aerial surveying techniques such as structure from motion photogrammetry are required. Furthermore, a range of resolutions will bridge the gap between SRTM and ground observations.

Here, we study two fault segments of the immature NNW-SSE striking Bilila-Mtakataka fault, Malawi, at the southern end of the East African Rift System. Previous studies concluded the Bilila-Mtakataka fault is geometrically continuous along its entire 100 km length, with the most recent event producing an average displacement of 10 m, equating to an Mw8.0 earthquake (JACKONSON & BLENKINSOP, 1997). We explore the extent to which differences in segment orientation and relationship to pre-existing structures (foliation) has influenced segment growth, leading to interaction. Our fault segments, near the village of Golomoti, have strikes differing on average by 10°, with a maximum of ~55° at their adjacent tips. The southern segment is sub-parallel to the foliation, while the northern segment is oblique to perpendicular to the locally folded foliation.

Fault scarp height and orientation is constrained by point cloud models derived from SRTM 30 m and Pleiades 0.5 m satellite data, and structure from motion using an Unmanned Aerial Vehicle (UAV). Displacement-length (D-L) analyses show bell-shaped appearances for both segments, with scarp height maxima (DMAX) closer to the adjacent tip than the segment centre. Skewed scarp height maxima suggests that this section of the Bilila-Mtakataka fault may be hard-linked and mechanically 'continuous' despite appearing as two geometrically-separate segments from ground observations. Coulomb stress change following earthquakes on the segments suggests that the foliation orientation is non-optimal for the growth of the northern segment, but optimal for the southern segment, potentially providing a pathway for linkage.

Our findings show that at certain angles to regional stress and fault strike, pre-existing structures influence fault growth and orientation, and geometrically separate fault segments may still be mechanically linked. Segment interactions may develop large, 'continuous' fault systems, increasing maximum fault rupture dimensions, and consequently, alter the seismic hazard.

Acknowledgements: This work was supported by the Natural Environment Research Council; Pleadies data was obtained through the Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET); fieldwork assistance was provided the Geological Survey Department, Malawi.

Reference

JACKSON, J., & BLENKINSOP, T., 1997. The Bilila-Mtakataka fault in Malawi: An active, 100-km long, normal fault segment in thick seismogenic crust. *Tectonics*, 16(1): 137-150.

Object-based time series analysis for landslide change detection using optical remote sensing imagery: Examples from Austria and Norway

Daniel Hölbling[1*], Max Koller[2], Florian Albrecht[1], Benjamin Aubrey Robson[2], Clemens Eisank[3] & Elisabeth Weinke[1]

[1] *Department of Geoinformatics - Z_GIS, University of Salzburg, Schillerstraße 30, 5020 Salzburg, Austria; daniel.hoelbling@sbg.ac.at*

[2] *Department of Geography, University of Bergen, P.O.Box 7800, 5020 Bergen, Norway*

[3] *GRID-IT - Gesellschaft für angewandte Geoinformatik mbH, Technikerstraße 21a, 6020 Innsbruck, Austria*

Key words: *landslides, remote sensing, object-based image analysis, time series analysis, Landsat, aerial photographs.*

Remote sensing imagery constitutes a valuable and cost-effective source for mapping landslides and identifying landslide changes. Just as the availability and quality of remote sensing data steadily increases, so do the demands for extracting relevant geospatial (change) information in a semi-automated or even fully automated manner. Facing the large number of sensor systems and processing techniques, however, it is a challenge to determine a suitable approach for time series analysis of optical imagery. Object-based image analysis (OBIA) enables us to work seamlessly with multi-scale geospatial data by combining image processing and GIS functionalities (BLASCHKE, 2010). Geomorphological features can be treated as aggregates of pixels and grouped into homogeneous image objects, providing not only spectral properties, but also information on topological relationships, size and shape. Object-based change detection (OBCD) offers unique methods for exploiting high resolution (HR) and very high resolution (VHR) imagery to capture meaningful detailed change information in a systematic and repeatable manner (CHEN *et al*., 2012; HUSSAIN *et al*., 2013). Even so, existing object-based methods are often customized to specific data or study areas. There is still need for research to improve their transferability across different sensors and scales, particularly when investigating complex natural phenomena such as landslides (HÖLBLING *et al*., 2015).

In this study an object-based time series analysis approach for detecting landslide changes in two different geographical regions is presented. The Austrian study site is located in the flysch of the Haunsberg area, approximately 10 km north of the city of Salzburg. This landslide-prone area has been known for a long time and is characterised by major landslides ("Fürwag landslide") that were particularly active during several years at the turn of the century (Fig. 1). For mapping the evolution of the Fürwag landslide, Landsat time series data from 1999 to 2003 is used. The second study site is close to the village of Flåm in the municipality of Aurland, western Norway (Fig. 2). The Flåm valley is a north-south oriented valley consisting predominantly of Precambrian gabbro-mangerite, gneisses and amphibolite overlain by phyllite and mica schist of Ordovician-Cambrian age, the latter section being of greater thickness on the eastern slope. Due to the structural differences and the disparity in resistance to weathering, landslide deposits show distinct difference in grain size and morphology. Landslide changes and debris accumulation areas as result of landslide activity are detected using aerial photographs from 2007 to 2014 with a spatial resolution ranging from 0.5 m to 0.1 m. The landslide changes are identified by comparing the transformation of feature values of segmentation-derived image objects between subsequent images. A major focus is put on the development of a method that is applicable to both study areas and the different data sets. Classification accuracies are assessed by a comparison to results from visual image interpretation, i.e. manually digitized reference polygons, to estimate the spatial overlap, under- and over-estimated areas.

The approach can be used for the regular update of landslide inventory maps. Moreover, findings from retrospective time-series analysis can provide useful information for predicting unstable areas prone to landslides and erosion. Such knowledge can be valuable for implementing prevention and mitigation measures to protect people and infrastructure.

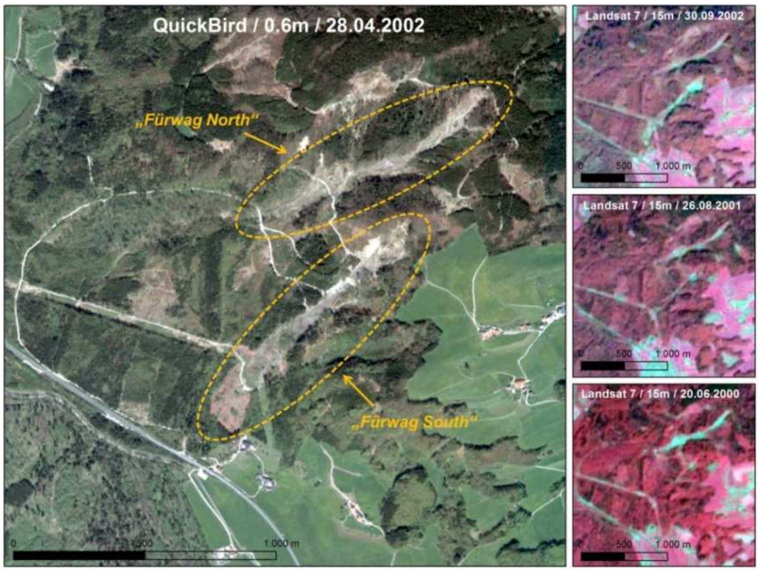


Figure 1: The Fürwag landslide in Austria. The two major landslides (“Fürwag North”, “Fürwag South”) are shown on a QuickBird image from 2002 for illustration purposes; corresponding Landsat 7 images from the years 2000, 2001 and 2002 that are used for time series analysis are shown on the right.

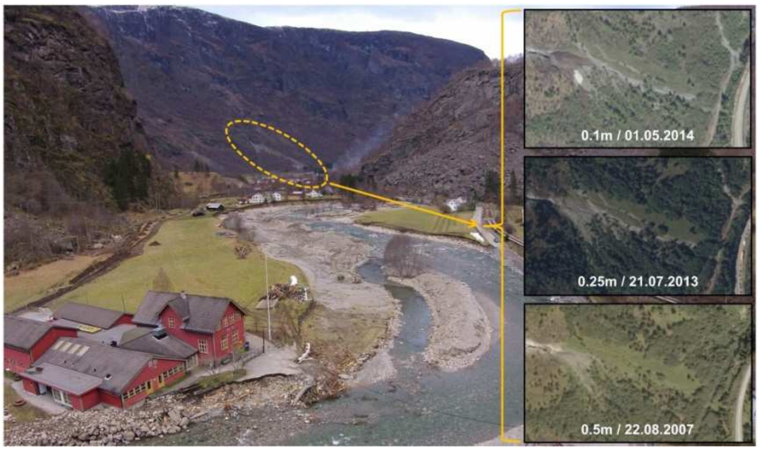


Figure 2: Photo (© Pål Ringkjøb Nielsen) from the Flåm valley and orthophotos from 2007, 2013 and 2014 showing changes in debris accumulation area.

Acknowledgements: This research has been supported by the Austrian Research Promotion Agency FFG in the Austrian Space Applications Program (ASAP 11) through the project “Land@Slide” (contract no: 847970) and the Academia Agreement (University of Bergen and Statoil).

References

BLASCHKE, T., 2010. Object based image analysis for remote sensing. *ISPRS Journal of Photogrammetry and Remote Sensing*, 65(1): 2-16.

CHEN, G., HAY, G.J., CARVALHO, L. & WULDER, M.A., 2012. Object-based change detection. *International Journal of Remote Sensing*, 33(14): 4434-4457.

HÖLBLING, D., FRIEDL, B. & EISANK, C., 2015. An object-based approach for semi-automated landslide change detection and attribution of changes to landslide classes in northern Taiwan. *Earth Science Informatics*, 8(2): 327-335.

HUSSAIN, M., CHEN, D., CHENG, A., WIE, H. & STANLEY, D., 2013. Change detection from remotely sensed images: From pixel-based to object-based approaches. *ISPRS Journal of Photogrammetry and Remote Sensing*, 80: 91-106.

Detection of surface water changes using TerraSAR-X data for flood hazard monitoring

Katherine Irwin[1*], Alexander Braun[1] & Georgia Fotopoulos[1]

[1] *Department of Geological Sciences and Geological Engineering, Queen's University, Canada; 0kei@queensu.ca*

Key words: *synthetic aperture radar, TerraSAR-X, water extent, flood hazards*

Identifying the presence, extent and change of surface water bodies is critical for determining potential flooding hazards. In this study, hazards caused by beaver activity are investigated. Currently, flooding and undermining hazards posed to nearby infrastructure such as railways are infrequently monitored by manned helicopter and ground-based field investigations. Satellite-based observations could present a viable alternative through the use of Synthetic Aperture Radar (SAR) with improved spatial and temporal coverage. Recently, a two-metre high beaver dam collapse caused a 15 m section of the Cataraqui Trail in Ontario to be completely washed out. This trail was built and maintained on an old railway line, which provides a testbed for determining the extent of damage such hazards can pose to critical infrastructure.

In this study, the single polarization (HH) backscatter intensity from TerraSAR-X (TSX) staring spotlight mode is used to map water extent. Water bodies are delineated as they exhibit very little backscatter and have good contrast with land targets (BRISCO *et al*., 2008). Grey-level thresholding is used to extract surface water bodies as well as wetlands. All pixels with a backscatter coefficient lower than a predefined threshold in an intensity image are mapped as water (WHITE *et al*., 2015). The backscatter intensity histogram and areas of known surface water are used to determine the threshold for each individual scene. Surface water thresholds ranged from 19.06 dB to 19.56 dB, and are scene specific as they are affected by seasonal conditions and incidence angle. Radar shadow and layover zones are also removed, as tall vegetation or infrastructure can block the signal from reaching the ground surface due to the side-looking nature of TSX. Using lidar elevation models to estimate the canopy height and simple geometry algorithms (MASON *et al*., 2010), these zones in the SAR data can be removed. The water cycle is analysed through a time series of water extent changes to better understand the net gain and loss of surface water.

The study area is located north of Kingston, ON, Canada, at the Queen's University Biological Station (QUBS). This area is mainly populated by lakes, small inland water bodies, marshland, open field, sparse forest and dense forest and has a history of beaver activity. Four TSX scenes have been acquired between April and May, 2016. SAR backscatter and grey-level thresholding have proven successful at delineating surface water from other land cover classes. Changes in water extent for scenes within the month of April are mainly due to increase in vegetation along shorelines and within vegetation-covered lakes (Fig. 1). Localized changes in water extent are analysed and correlated to precipitation, beaver, or other anthropogenic activity. Terrestrial and airborne lidar, optical imagery, and in-situ field observations assisted in the validation. The conclusions and techniques developed in this study will be applicable to other areas where similar conditions and data exist.

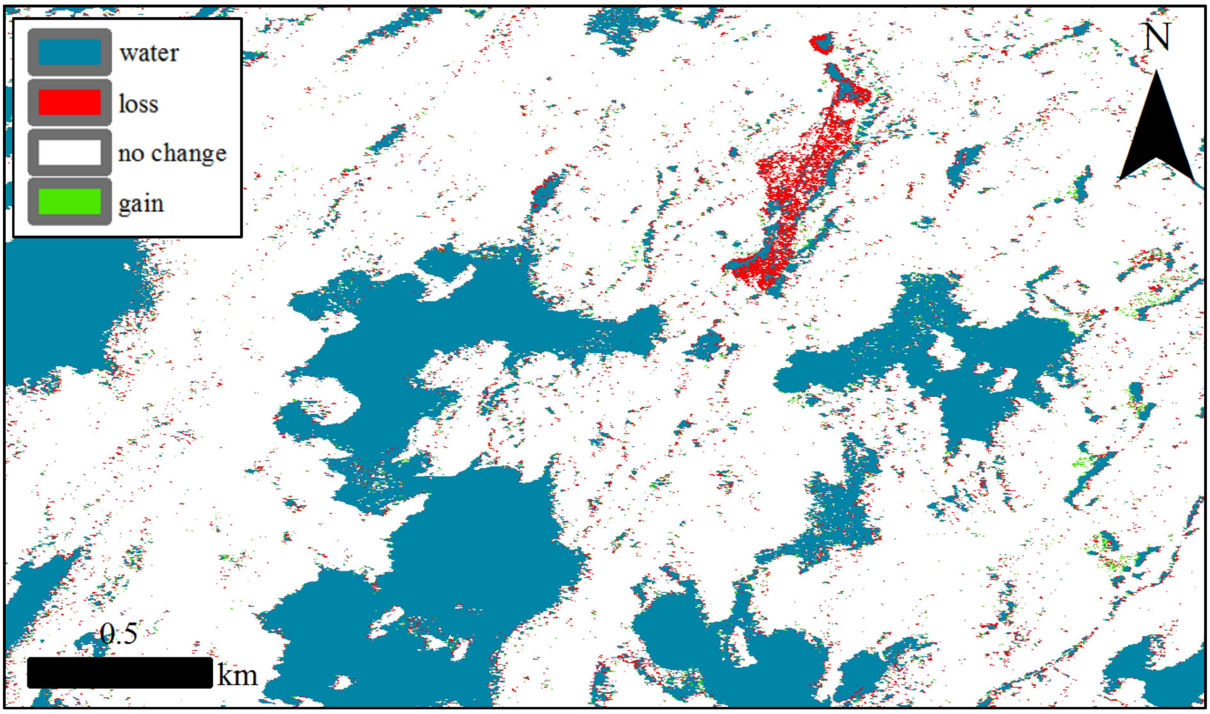


Figure 1: Radar derived change detection map of surface water (blue) and non-water (white) over QUBS using TSX data from April 2, 2016 and April 24th, 2016. Red, green and white indicate net loss, net gain and no change in surface water between April 2nd, 2016 and April 24th, 2016. Top, Right of Centre: Large area of net loss of surface water due to increase in vegetation on shallow lake.

References

BRISCO, B., TOUZI, R., VAN DER SANDEN, J., CHARBONNEAU, F., PULTZ, T., D'IORIO, M., 2008. Water resource applications with RADARSAT-2 – a preview. *International Journal of Digital Earth*, 1(1): 130-147.

MASON, D., SPECK, R., DEVEREUX, B., SCHUMANN, G., NEAL, J, BATES, P., 2010. Flood detection in urban areas using TerraSAR-X. *IEEE Transactions in Geoscience and Remote Sensing*, 48(2): 882-894.

WHITE, L., BRISCO, B., DABBOOR, M., SCHMITT, A., PRATT, A., 2015. A collection of SAR methodologies for monitoring wetlands. *Remote Sensing*, 7: 7615-7645.

Time-lapse cameras and structure from motion algorithms: Continuous three-dimensional monitoring in geosciences

Andreas Kaiser[1*], Fabian Neugirg[2], Anette Eltner[3], Florian Haas[2] & Jürgen Schmidt[1]

[1] *Soil and Water Conservation Unit, Technical University Freiberg, 09599 Freiberg, Germany; andreas.kaiser@tbt.tu-freiberg.de*

[2] *Dept. of Physical Geography, Catholic University Eichstätt-Ingolstadt, 85072 Eichstätt, Germany*

[3] *Institute of Photogrammetry and Remote Sensing, Technical University Dresden, 01067 Dresden, Germany*

Key words: *structure from motion, time-lapse, 4D, erosion monitoring.*

Time-lapse cameras enable fascinating visual insights into earth surface processes only by compressing time. Their applications are diverse and offer interesting opportunities for scientific usage. Especially in geosciences they help to document and analyse processes in high temporal resolution. Due to rapid developments in computer vision and photogrammetry, an array of multiple cameras allows for surface reconstruction of any area of interest. Installing a time-lapse system with a multi-angle camera setup can thus enable repeated calculation of digital elevation models (DEMs) of difference. The main benefits of such a setup lie in the continuous 4D monitoring of geomorphic processes.

We present two examples of different installations, in an Alpine catchment and on an agricultural site. While the Alpine setup helps to identify and quantify a variety of slope shaping processes, the cameras in the agricultural site observe the impact of heavy rainfall events on rill forming and sheet erosion. As well as high temporal resolution, high spatial resolution is achieved due to the proximity of cameras to the areas of interest. Referencing of the DEMs is realised in a local coordinate system using fixed reference points. Despite the promising results of the approach, multiple logistical challenges must be tackled in advance of setting up the autonomous systems, i.e. synchronization of camera triggers, energy supply under harsh conditions and movement of the cameras.

Nevertheless, besides the continuous visual proof of processes, the study allowed for the derivation of mass fluxes in the research areas. Furthermore, observations serve as validation data for event-based erosion modelling, as the data is available for in-situ events.

Acknowledgements: The presented study was partially funded by the German Research Foundation (DFG grant numbers: SCHM 1373/8-1, HA 5740/3-1, MA 2504/15-1).

Collaborative and immersive analytics to support stratigraphic survey

Demetrius Nunes Alves[1], Lais Vieira de Souza[1], Marcelo Kehl de Souza[1,2*], Leonardo Campos Inocencio[1*], Mauricio Roberto Veronez[1,2*], Luiz Gonzaga Jr.[1,3], Felipe Rocha Wagner[1], Fernando P. Marson[1] & Alipio José Pereira[4]

[1] *Advanced Visualization Laboratory (VizLab), Vale do Rio dos Sinos University (UNISINOS), São Leopoldo, Brazil, veronez@unisinos.br*

[2] *Graduate Program in Geology, Vale do Rio dos Sinos University (UNISINOS), São Leopoldo - RS – Brazil*

[3] *Graduate Program in Applied Computing, Vale do Rio dos Sinos University (UNISINOS), São Leopoldo - RS – Brazil*

[4] *PDGEO/GSE - CENPES - PETROBRAS, Rio de Janeiro, Brazil*

Key words: *computer vision, head-mounted display, outcrop, collaborative environment.*

Geological studies are commonly supported by 3D modelling techniques, but very few researchers make use of fully immersive 3D visualization techniques to inspect outcrops. The main objective of this research is to introduce a collaborative and immersive 3D visualization approach to support stratigraphic studies using a head-mounted display (HMD) to explore a 3D virtual model of an outcrop in Fazenda Arrecife (Salitre Formation, Neoproterozoic), State of Bahia, Brazil. The outcrop is composed of columnar stromatolite fossils embedded in carbonate sediments, showing evidence of storm action. This outcrop is an important geological-paleontological site that has contributed to the regional paleogeographic reconstruction, also being in analogous studies of oil and gas reservoirs (ENGE et al., 2007). For this, we have developed a methodology that makes use of multiple RGB-images to reconstruct the 3D content, and integrate it into a fully immersive/interactive visualization environment to support to geological and paleontological studies.

During fieldwork, we have taken highly overlapping photos. Then, 3D the virtual model was reconstructed and georeferenced by known geodetic coordinates. The 3D model has been reconstructed through SfM (structure from motion), georeferenced, edited and partitioned to improve interactivity (SIMA et al., 2012). The prototype has been developed based on a rapid methodology to various system platforms, including desktop, HMD, and mobile. A game controller allows users moving on the virtual environment, while internal HMD gyroscope and accelerometer reacts to the user's head movements, providing a correct feedback to explore virtual environment around him/her. The immersive visualization of the outcrop model shows the similar structure, texture and illumination observed on the fieldwork, scaled to real size. This application allows the smooth visualization and inspection of fossils and depositional structures in a fully immersive and user-friendly environment. Also the prototype allows to store persistently the 3D model, and share the analysis of the entire data, through a fully immersive computational environment with high precision, low-cost and cooperatively.

Figure 1: The system prototype, highlighting a) user interacting with the application through head-mounted display and game controller; b) infrared view of the Head Mounted Display, where red points are part of the HMD tracking system; c) virtual 3D outcrop model, obtained by multiple images and SfM techniques.

Acknowledgements: This project was financially-supported by FINEP Agency (MCT/FINEP - Pré-Sal Cooperativos ICT - Empresas 03/2010 - Contract 01.23.4567.89), PROSUP/CAPES for the financial support of the PhD scholarship.

References

ENGE, H.D., BUCKLEY, S.J., ROTEVATN, A. & HOWELL, J.A., 2007. From outcrop to reservoir simulation model: Workflow and procedures. *Geosphere*, 3: 469-490.

SIMA, A.A., BUCKLEY, S.J. & VIOLA, I., 2012. An interactive tool for analysis and optimization of texture parameters in photorealistic virtual 3D models. *International Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, I(2): 165-170.

Digital taphonomic model as a tool to improve viewing of a bivalve mollusc-dominated fossil biofabric

Rodrigo Scalise Horodyski[1], Hugo Schmidt-Neto[1], Demetrius Nunes Alves[2], Maurício Roberto Veronez[2*,3], Luiz Gonzaga Jr.[2,4], Leonardo Campos Inocencio[2], Felipe Rocha Wagner [2] & Marcelo Kehl de Souza[2,3*]

[1] Laboratory of Paleontology Applied, Graduate Program in Geology, Vale do Rio dos Sinos University, (UNISINOS), São Leopoldo, Brasil
[2] Advanced Visualization Laboratory (VizLab), UNISINOS, São Leopoldo, Brazil, veronez@unisinos.br
[3] Graduate Program in Geology, UNISINOS, São Leopoldo, Brazil
[4] Graduate Program in Applied Computing, UNISINOS, São Leopoldo, Brazil

Key words: *paleontology, taphonomy, biofabric, 3D fossil, structure from motion.*

Biofabric refers to the three-dimensional taphonomic arrangement of skeletal elements in the matrix, include orientation, close packing, and sorting by size and shape (KIDWELL & HOLLAND, 1991). The biofabric depends primarily on the hydrodynamics of hard part concentration and sedimentation rate, but it may also reflect rotation and disarticulation of elements during compaction. The taphonomic elements are perpendicular, oblique and/or concordant to the bedding plane. A virtual three-dimensional fossil assemblage can allow better visualization and interpretation of the taphonomic elements. Thus, the aim of this research is to employ computer vision techniques to reconstructing 3D model of samples. In our experiment, the sample used comprises a marine bivalve mollusc-dominated fossil assemblage, and is preserved in the fine-grained sandstones of the Paraguaçu Member (Rio Bonito Formation, Lower Permian, Paraná Basin, Brazil; see SCHMIDT-NETO *et al*., 2014). The developed prototype has been capable to estimate position and orientation (poses) for every photo using structure from motion (SfM) by detecting and matching common features between photos. The scene containing the poses of every photo is used to compute points, geometry and texture. Afterwards undesired geometries are removed and the model is ready for analysis. As seen in Fig. 1 the three-dimensional visualization allows to recognize that the bivalved skeletal have different sizes, disarticulated, matrix-supported biofabric, a few in direct contact, and poorly sorted.

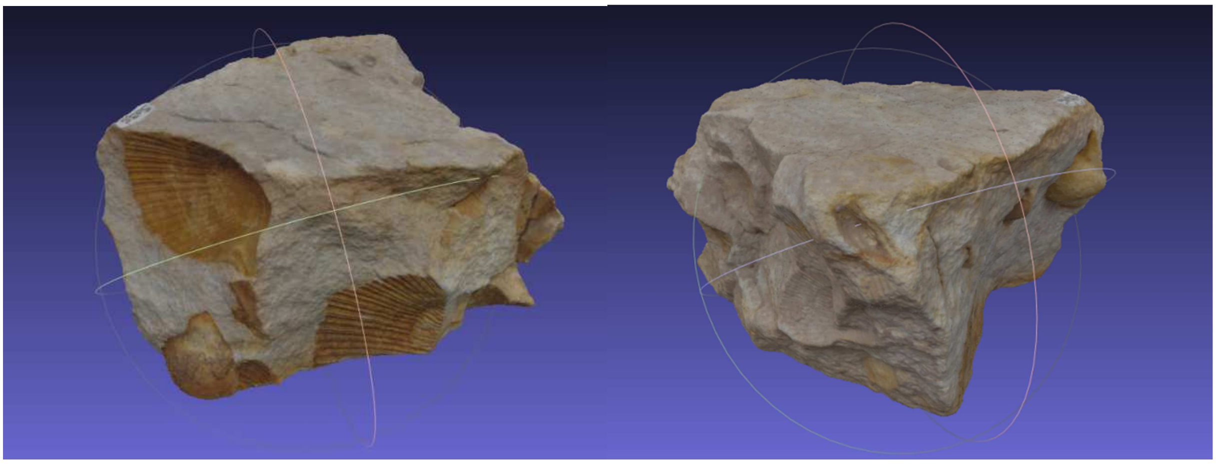


Figure 1: 3D reconstruction of our sample viewed from two angles.

These taphonomic features provided important clues to genesis. The taphonomic features revealed that this fossil assemblage is parautochthonous, and the bioclast accumulations represent shell beds formed by high frequency storm events, being quickly buried in the shoreface. The digital taphonomic model proved to be very useful, to stimulate knowledge, to ease the taphonomic feature recognition, and to develop a three-dimensional database of designs for geosciences.

Acknowledgements: This project was financially supported by the projects Modelagem Digital de Afloramentos utilizando GPU (MCT/FINEP - Pré-Sal Cooperativos ICT - Empresas 03/2010 - Contract 01.23.4567.89). RSH thanks PNPD/CAPES for the financial support of the PhD scholarship. MRV thanks the Brazilian Council for Scientific and Technological Development (CNPq) for the research grant (Process 309399/2014-9).

References

KIDWELL, S.M., & HOLLAND, S.M., 1991. Field description of coarse bioclastic fabrics. *Palaios*, (6): 426-434.

SCHMIDT-NETO, H., NETTO, R.G. & TOGNOLI, F.M.W., 2014. Análise tafonômica das concentrações fossilíferas da Formação Rio Bonito na região de Taió, Sul do Brasil. *Revista Brasileira de Paleontologia*, 17(2): 207-224.

Low-cost 3D scanning technique for digital outcrop modelling based on multiple view images

Luiz Gonzaga Jr.[1,2], Maurício Roberto Veronez[1,3], Reginaldo Macedônio da Silva[1], Luiz Paulo Luna de Oliveira[2], Francisco Tognoli[3], Felipe Rocha Wagner[1], Marcelo Kehl de Souza[1*] & Fabiane Bordin[1]

[1] *Advanced Visualization Laboratory (VizLab), Vale do Rio dos Sinos University (UNISINOS), São Leopoldo, Brazil, veronez@unisinos.br*
[2] *Graduate Program in Applied Computing, UNISINOS, São Leopoldo, Brazil*
[3] *Graduate Program in Geology, UNISINOS, São Leopoldo, Brazil*

Key words: *laser scanning, multiple view geometry, structure from motion, digital image, 3D reconstruction, digital outcrop model.*

This paper presents a low-cost 3D scanning technique for digital outcrop modelling based on multiple raster images, jointly with a 3D reconstruction algorithm, capable to provide high quality results. To make the method feasible, we have performed a comparative study about 3D reconstruction based on active and passive sensors, mainly lidar – terrestrial laser scanner (TLS) and raster images (photography), respectively. An accuracy analysis has been performed in the positioning of outcrop point clouds obtained by both techniques. A Hausdorff metric has been adopted to compare two point clouds of the same target using both acquisition methods. To make the comparison feasible, datasets are composed by point clouds generated from multiple images in different poses using a consumer digital camera and directly by terrestrial laser scanner. After pre-processing stages to obtain these point clouds, both are compared, through the positional discrepancies and standard deviation, and Hausdorff distance. The preliminary analysis have shown multiple digital images jointly 3D reconstruction method to be an alternative 3D scanning technique for digital outcrop modelling, concerning with data acquisition at low cost without significantly loss of accuracy when compared with lidar.

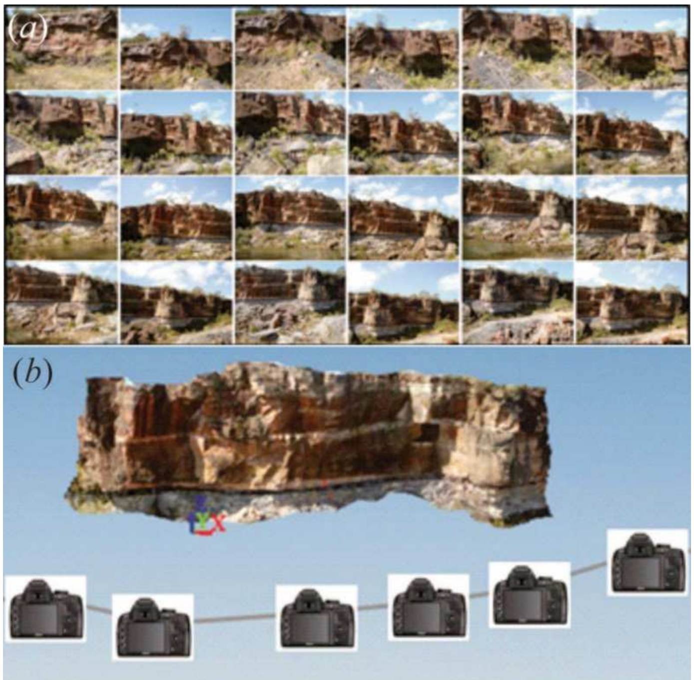


Figure 1: Pictures obtained with the camera (a). Illustration of camera's position (b).

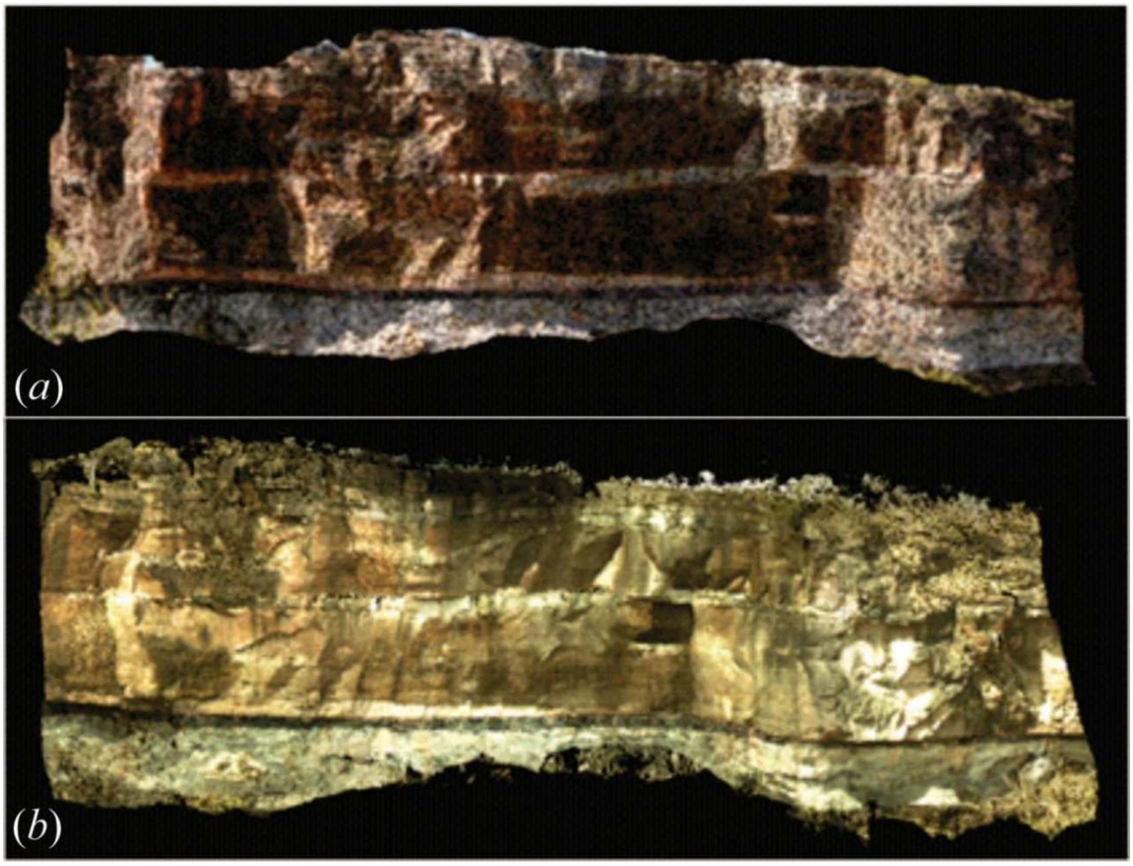


Figure 2: 3D Reconstruction from photos (a) and terrestrial laser scanner (b).

Acknowledgements: This project was financial supported by FINEP Agency (MCT/FINEP - Pré-Sal Cooperativos ICT - Empresas 03/2010 - Contract 01.23.4567.89), PROSUP/CAPES for the financial support of the PhD scholarship.

Multispectral spectroscopy as a tool for detection of surfaces and stacking patterns in a carbonate-siliciclastic basin to support sequence stratigraphy

Marcelo Kehl de Souza[1,2*], Maurício Roberto Veronez[1,2], Luiz Paulo Luna de Oliveira[1,3], Luiz Gonzaga Jr.[1,3], Joice Cagliari[2], Marco Scaioni[4], Mateus R. de Vargas[2] & Arel H.R. Antonio[2]

[1] Advanced Visualization Laboratory (VizLab), Vale do Rio dos Sinos University (UNISINOS), São Leopoldo, Brazil, veronez@unisinos.br
[2] Graduate Program in Geology, UNISINOS, São Leopoldo, Brazil
[3] Graduate Program in Applied Computing, UNISINOS, São Leopoldo, Brazil
[4] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italy

Key words: *imaging spectroscopy, principal component analysis, sequence stratigraphy, carbonate-siliciclastic mix.*

We investigated the potential of multispectral satellite data as a tool for detection of surfaces and stacking patterns to support sedimentary studies. To do so, we conducted a field spectral sedimentological survey and spectral image processing on SWIR wavelengths in a Neuquén Basin outcrop, Argentina. The studied sedimentary record presents over 600 m of exposition length and encompasses siliciclastic, evaporate, and carbonate rocks. The chosen ASTER scene was atmospherically and radiometrically-adjusted and processed using Principal Component Analysis (PCA) in the SWIR (band 5 to 9) (Fig. 1). PC1 values present nearly continuous values in the studied bands and are related to the brightness. PC2 values show the relationship between the main absorption features of the measured spectrums. Wavelengths of 2.2 µm, typical of the clay minerals, in the Avilé sandstone and 2.33 µm, typical of the calcite, in the limestone. PC3 values present a decrease towards the longest wavelengths.

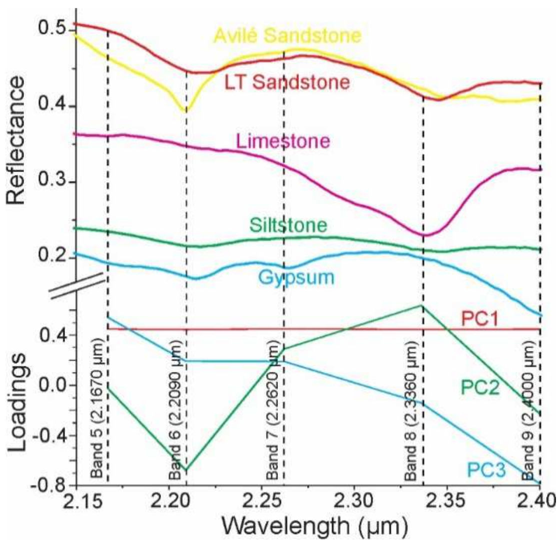


Figure 1: The spectrums of the main rocks measured in field and the PC1, PC2, and PC3 loadings of Aster data processing. Abbreviation: LT (Lower Troncoso).

The first principal component (PC1) is related to the brightness and represents over 96% of data variance. The second principal component (PC2) was shown to be efficient in distinguishing between siliciclastic and carbonate rocks, in a typical basin with mixed sedimentary record, with siliciclastics in the highest values and carbonates in the lowest values. Using the PC RGB composition, it was possible to distinguish important stratigraphic surfaces and four transgressive-regressive cycles within the Agua de la Mula member, as shown as

Fig. 2. At the base, the sequence boundary (SB1 – Coihuéquica unconformity) between the Pilmatué and Avilé members; the first transgressive surface (TS1) the limit between the Avilé and Agua de la Mula members; four transgressive surfaces (TSa, TSb, TSc, and TSd), indicating four great transgressive-regressive cycles, inside the Agua de la Mula Member. Pampatrílica regional unconformity, between the Agua de la Mula Member and the Lower Troncoso Member (SB2); and at the profile top, the transgressive surface, between the Lower Troncoso and Upper Troncoso Member (TS2) was also possible to distinguish.

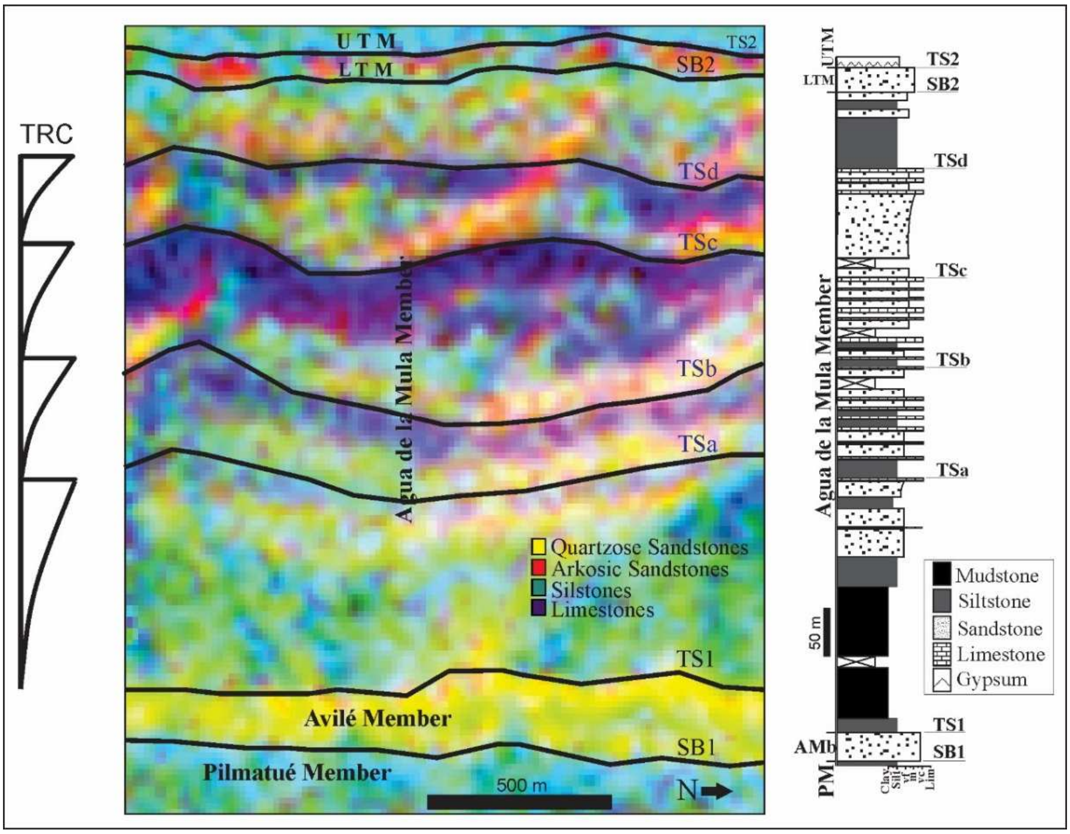


Figure 2: Interpretation of the main surfaces identified in the RGB composition of PC1, 2 and 3. On the right, the sedimentological profile data collected in field. Abbreviations: TRC (Transgressive-Regressive Cycles), LTM (Lower Troncoso member), UTM (Upper Troncoso Member), AMb (Avilé Member), PM (Pilmatué Member), SB (Sequence Boundery), TS (Transgressive Surface).

The results show the potential of this technique to complement traditional sedimentary basin research, whereas it was possible to distinguish between siliciclastic and carbonate rocks, to identify surfaces, and transgressive-regressive cycles in a mixed sedimentary record. The result is an inexpensive, fast and non-invasive method to support more complex and detailed stratigraphy studies.

Acknowledgements: This project was financially supported by the projects Modelagem Digital de Afloramentos utilizando GPU (MCT/FINEP - Pré-Sal Cooperativos ICT - Empresas 03/2010 - Contract 01.23.4567.89) and FINEP-PROINFRA (Contract: 01.13.0302.00). MKS thanks PROSUP/CAPES for the financial support of the PhD scholarship. MRV thanks the Brazilian Council for Scientific and Technological Development (CNPq) for the research grant (Process 309399/2014-9).

Reflectance spectroscopy applied to the lithological characterization of Permo-Carboniferous siltstones and organic shales found in the Paraná Basin, Brazil

Laís V. Souza[1], Marcelo Kehl de Souza[1*], Maurício Roberto Veronez[1,2], Francisco Tognoli[1,2], Luiz Paulo Luna de Oliveira[1,3] & Luiz Gonzaga Jr.[1,3]

[1] *Advanced Visualization Laboratory (VizLab), Vale do Rio dos Sinos University (UNISINOS), São Leopoldo, Brazil, veronez@unisinos.br*
[2] *Graduate Program in Geology, UNISINOS, São Leopoldo, Brazil*
[3] *Graduate Program in Applied Computing, UNISINOS, São Leopoldo, Brazil*

Key words: *Reflectance spectroscopy, PCA, Paraná Basin, sedimentary rocks, organic matter.*

This paper shows the application of reflectance spectroscopy in the characterization of siltstones and organic shales in different lithostratigraphic units (e.g. formation, group). Naked eye observation and characterization can be difficult when describing and comparing these rocks in distinct units, since sedimentary rocks of fine granulometry present very similar physical properties. Other factors could also aggravate its identification in field, especially in tropical regions that present a more humid climate, such as the degree of weathering of the outcrop or the contact between two formations. The spectral analysis of these lithologies is not yet widely studied, since the presence of organic matter makes the reflectance patterns in the spectral curve much lower and with no characterizing absorption features. Thus, a methodology that facilitates the recognition and classification of fine granulometry rocks represents progress in the field of sedimentary petrology, which currently makes use of microscopic, geochemical and geophysical techniques. The reflectance spectroscopy technique provides a quantitative measure of the spectral reflectance of materials that is obtained by the ratio between radiance and irradiance. By using the spectral signature, it is possible to identify the main characteristics of the absorption features of the minerals found and thus recognize constituent elements and/or classify such rocks. The objectives of this research are: 1) to search for patterns that characterize each sample/lithostatigraphic unit using its spectral behaviour, also identifying the main absorption features of the fine granulometry rocks that present organic matter in their composition; 2) to test the possibility of distinguishing and grouping together each formation by its spectral behaviour using a classifier. To do so, 45 samples of lithostratigraphic units were selected, representing part of the permo-carboniferious succession of the Paraná Basin - Brazil, such as the Rio do Sul, Palermo, and Irati Formations. All samples were ground to a size smaller than the silt fraction (0.062 mm) and the ground sample measurements were made with a SPECTRAL EVOLUTION field spectroradiometer, type SR-3500, which records the spectral pattern in the wavelength interval from 350 to 2500 nm. Initial results show that the samples of each formation present distinct spectral responses, even when they present very similar physical characteristics (Fig. 1). Spectral data obtained through Principal Component Analysis (PCA) show that the samples are classified into three distinct groups (Fig. 2). This technique has shown to be effective for lithological differentiation, as the spectral reflectance is directly related to the chemical properties of the rocks, which are distinct for each formation and too subtle to be perceived by naked eye analysis.

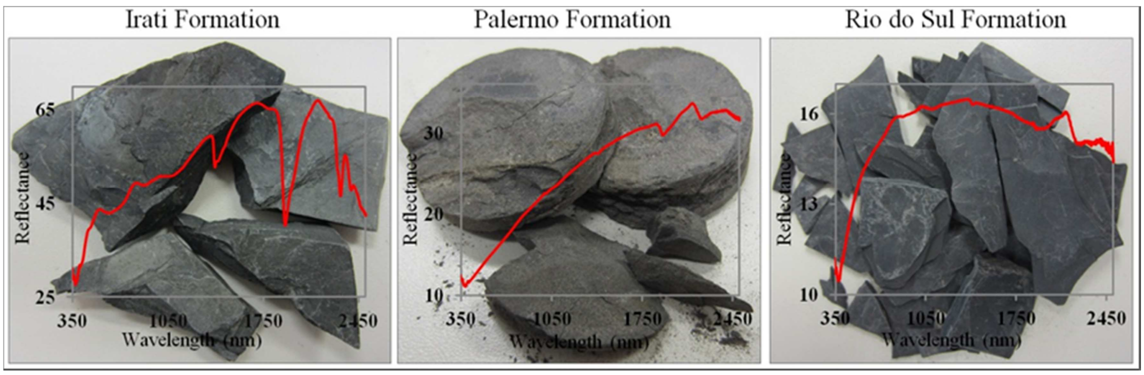


Figure 1: Average spectral curves of siltstones and shales organic of the formations studied.

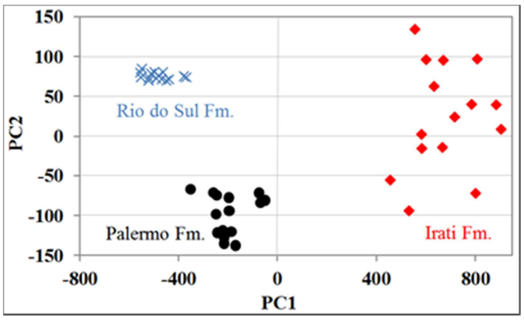


Figure 2: PC1 versus PC2. It is possible to note the data clustering of each formation, mainly in PC1 values.

Acknowledgements: This project was financially supported by the projects Modelagem Digital de Afloramentos utilizando GPU (MCT/FINEP - Pré-Sal Cooperativos ICT - Empresas 03/2010 - Contract 01.23.4567.89) and FINEP-PROINFRA (Contract: 01.13.0302.00). MKS thanks PROSUP/CAPES for the financial support of the PhD scholarship. MRV thanks the Brazilian Council for Scientific and Technological Development (CNPq) for the research grant (Process 309399/2014-9).

Unravelling the structure of the ocean-continent transition from high resolution, photo-based 3D reconstructions of onshore dyke complexes

Moritz Kirsch[1*], Andreas Kaiser[2] & Anette Eltner[3]

[1] *Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institut Freiberg für Ressourcentechnologie, Chemnitzer Straße 40, 09599 Freiberg, Germany; m.kirsch@hzdr.de*
[2] *AG Boden- und Gewässerschutz, TU Bergakademie Freiberg, Agricolastraße 22, 09599 Freiberg, Germany*
[3] *Institut für Photogrammetrie und Fernerkundung, Technische Universität Dresden, Helmholtzstraße 10, 01069 Dresden, Germany*

Key words: *structure from motion, photogrammetry, structural geology, rifting.*

The temporal and spatial partitioning of strain between faulting and magmatism during continental breakup has important implications for the development of the crust- and upper mantle structure at rifted margins, but remains poorly understood. Late Neoproterozoic basaltic dyke complexes emplaced into continental basement and sedimentary cover units in the northern Scandinavian Caledonides represent an onshore-analogue of an ocean-continent transition. The dykes and their host rocks are largely unaffected by Caledonian deformation and metamorphism, and are excellently exposed in three dimensions owing to a combination of glacial dissection and glacial retreat. Many of these outcrops of potentially high scientific value remain unmapped, mainly because they occur along steep, up to 300 m high, ridges of glacier cirques in rugged mountain terrain that is largely inaccessible for traditional field mapping. Combined terrestrial and UAV-based structure from motion (SfM) photogrammetry provides an accurate and quick method of obtaining high resolution 3D information of such outcrops with minimal logistical effort. SfM-derived point clouds can be processed to identify structural discontinuities, such as faults and lithological contacts, and extract parameters such as strike, dip, thickness, density, and relative sequence of emplacement of the dykes. Based on this information, the history of progressive intrusion and tilting can be reconstructed, and the amount of tectonic extension vs. magmatic dilation estimated. To demonstrate the effectiveness of this approach, we present a case study from a quarry in Lusatia, Germany. Here, as in northern Scandinavia, several generations of cross-cutting basalt dikes are exposed along a vertical, rocky cliff, but with the benefit of easy accessibility, permitting direct observation and verification of the digital data with field measurements. To improve accuracy, and to allow the extraction of oriented and scaled data as well as draping of independently-acquired spectral data, ground control points are established in the scene using total station surveying. Multi and hyperspectral data will potentially be used as complementary information to accurately distinguish composite dikes lacking intervening screens of host rock.

Application of photogrammetry for mapping of natural solution collapse breccia pipes in the Grand Canyon, USA

Matthias Klawitter[1,2*], Davide Pistellato[2], Anthony Webster[1] & Joan Esterle[2]

[1] University of Queensland, Sustainable Minerals Institute – WH Bryan Mining & Geology Research Centre, Brisbane, Australia; m.klawitter@uq.edu.au

[2] University of Queensland, School of Earth Science, Brisbane, Australia

Key words: *photogrammetry, 3D modelling, structural analysis, mapping, solution collapse breccia pipes.*

The Colorado Plateau in northern Arizona, USA, hosts hundreds of solution collapse breccia pipes (SCBP) and sinkholes (BROWN & BILLINGSLEY, 2010). These structures formed due to the dissolution of limestone, which formed an extensive cave system. Eventually the ceiling of the cave failed and the overlying rock dropped into the void. If the collapse occurred immediately below the surface, it formed a sinkhole; if it originated at a deeper stratigraphic level, followed by an upward stopping process through the overlying strata, a vertical pipe-like structure was formed (SCBP), which is filled with angular to rounded fragments of broken rock (WENRICH & TITLEY, 2008). Erosional processes started forming the Grand Canyon 5 Ma ago and exposed some parts of these structures at different stratigraphic levels, allowing them to be investigated. Further, sinkholes formed in the same strata and were studied as a means of possible understanding of the original surface expression of a SCBP.

The best exposures of SCBPs are in remote cliff faces and thus are not accessible. To study these structures, close range digital photogrammetry, a remote sensing technique, was used for data acquisition. Photogrammetry is based on capturing two photos of the same area from two different locations. Software packages, such as Agisoft PhotoScan, identify identical reference points in each photo and accordingly intersect these photos to create a 3D image. This, combined with high precision topographic measurements recorded by Differential GPS, allows the generation of correctly scaled and georeferenced 3D models from 2D imagery (Fig. 1).

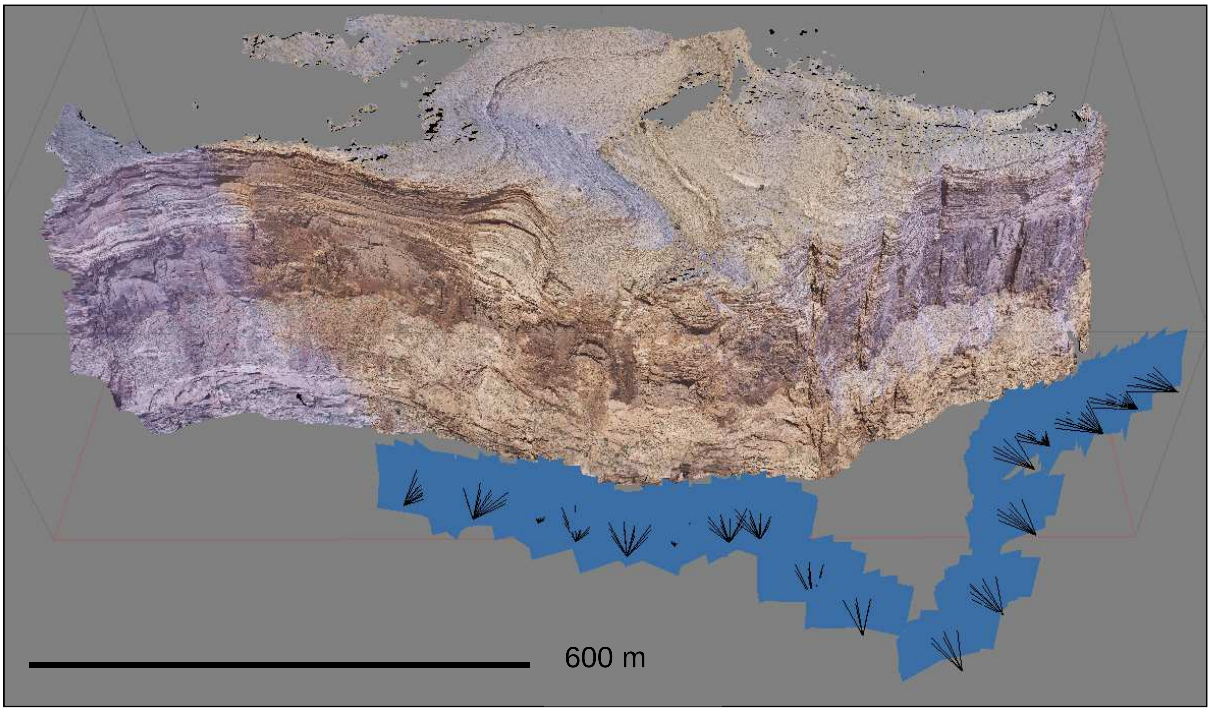


Figure 1: 3D photogrammetry model of a canyon wall from a side branch of the Grand Canyon in central northern Arizona, U.S.A. The blue shapes indicate the camera positions of the other side of the canyon from where the photos were taken. The cameras were set up in a specific way to create as much overlap as possible and to cover as much of the canyon wall as possible to obtain a highly detailed 3D model of the canyon wall. The white arrow indicates the location of the SCBP.

The final 3D photogrammetry models obtained of exposed SCBPs are highly suitable for post-processing. Additional software packages, such as Maptek I-Site and Maptek Vulcan, assist in the structural and geotechnical analysis (Fig. 2) to investigate and map key geological features of the rock mass, such as discontinuities (e.g. fractures, joints, bedding planes, etc.) and properties of the broken material (e.g. block size, size distribution, shape, orientation, etc.).

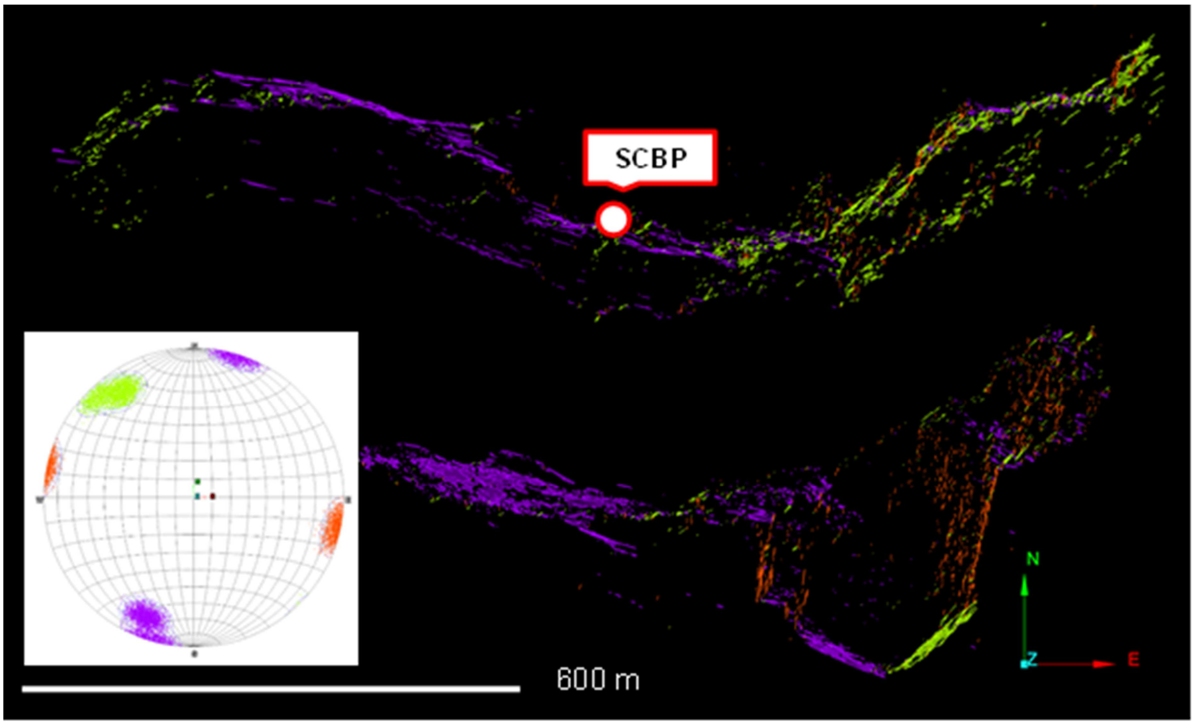


Figure 2: Aerial view of the three major discontinuity sets from the northern and southern canyon walls extracted from the 3D photogrammetry model (Figure 1). The red/white dot indicates the location of the SCBP. The pipe boundaries exposed in the canyon walls strike 196° to 198° degrees parallel to the N/S trending local fault sets.

The study has shown that the occurrence and development of these systems is structurally controlled at all scales, while the surrounding lithology may also influence the geometry of a SCBP. Regardless of the location on the Colorado Plateau, every SCBP and sinkhole examined, develops parallel or perpendicular to the trend of the local fault systems and fails along the joint sets in the host rocks. The jointing and changes in the surrounding lithology influences the rheology and failure behaviour of the rock mass, resulting in different sizes and shapes of the broken material in the 'breccia' column. Further, the research is revealing different zones of particle flow within the pipes, indicating that the genesis of a SCBP happened over multiple stages, and not as one catastrophic event.

Acknowledgements: The authors of this study would like to acknowledge Dan Wood, John Dreier, George Billingsley, Donn Pillmore, Matthew Germansen, the Navajo Nation and the U.S. National Park Service.

References

BROWN, K.M. & BILLINGSLEY, G.H., 2010. Map showing geologic structure, cultural and geographic features, and geologic cross sections of northwestern Arizona. *U.S. Geological Survey, Scientific Investigations Report 2010-5025*, Plate 1, scale 1:375,000.

WENRICH, K.J. & TITLEY, S.R., 2008. Uranium exploration for northern Arizona (USA) breccia pipes in the 21st century and consideration of genetic models. In SPENCER, J.E., & TITLEY, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geological evolution, and ore deposits: *Arizona Geological Society Digest*, 22: 295-309.

The 3D visualization and analysis of fracturing by using laser scanning data, geological maps and geophysical data: Study sites from Southern Finland

Eevaliisa Laine[1*] & Mira Markovaara-Koivisto[1]

[1] *Geological Survey of Finland, Bedrock construction and site assessment, Espoo, eevaliisa.laine@gtk.fi*

Key words: *laser scanning, fracture network modelling, geoscience, Finland, 3D visualization.*

Rock fracturing affects directly rock properties, for example dissemination of metals and pollutants in the groundwater, thermal conductivity through water flow and rock stability. The purpose of the present study was to combine statistical analysis of fracture properties and 3D visualization tools in analysing fracturing of Precambrian bedrock in southern Finland and, finally, to build a workflow for fracture network modelling. Laser scanning technology is based on laser pulses sent by a laser scanner and on precise positioning. The National Land Survey produces an elevation model in grid size 2 m x 2 m from the laser scanning data. The accuracy of the elevation is ±0.3 m in most of the laser scanned areas, and ±0.3-1 m in minority due to vegetation. The elevation model covers ca. 70% of Finland. The used geological data and low altitude geophysical maps are from the Geological Survey of Finland databases. The study sites included Palmottu and Kopparnäs areas. The first example area was Palmottu which have been studied during uranium exploration phase in the early 1980s and later during the Palmottu Natural Analogue Project 1994-1998 (AHONEN *et al*., 2004). The second example site was Kopparnäs also studied for nuclear waste investigations (JÄÄSKELÄNEN *et al*., 2005).The geology of Kopparnäs and Palmottu areas are typical for southern Finland. The rocks are mainly composed of granites, granodiorites and mica gneiss and are characteristically migmatic. The fractures and faults could be interpreted from the detail elevation models (Palmottu example in the Fig. 1). The interpreted faults and fractures from elevation models and geophysical maps were combined and validated using direct geological observations from outcrops and drill core logs. Spatio-statistical analysis of these combined fracture data were used in building 3D fracture network. So, the final workflow for fracture network modelling includes spatio-statistical analysis and 3D visualization of interpreted fractures and faults.

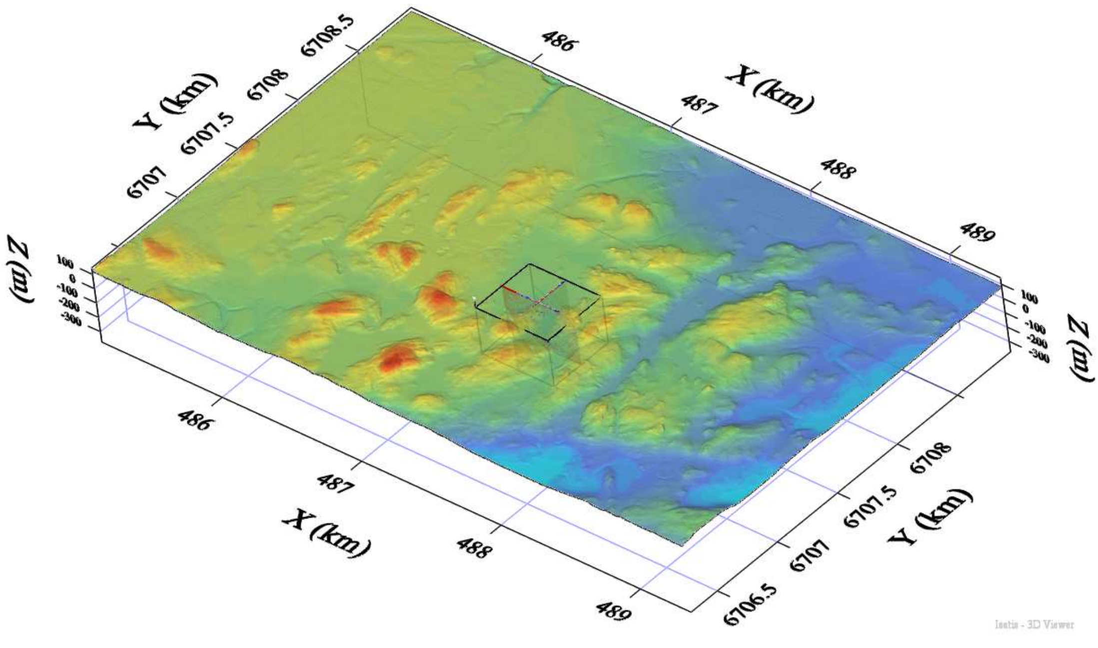


Figure 1: Palmottu site and digital elevation data (© National Land Survey of Finland). The visualization was done using ISATIS 3D viewer.

References

AHONEN, L., KAIJA, J., PAANANEN, M., RUSKEENIEMI, T. & HAKKARAINEN, T., 2004. Palmottu natural analogue: A summary of the studies. *Geological Survey of Finland, Report YST-121*, 39 pages, 1 appendix. ISBN 951-690-896-9, ISSN 0783- 3555.

JÄÄSKELÄINEN, P. AND KORHONEN, KIMMO, 2005. Studies at Kopparnäs in 2004. *Geological Survey of Finland, Report YST-122*, 41 pages. ISBN 951-690-936-1, ISSN 0783-3555.

Rockfall monitoring of a poorly consolidated marly sandstone cliff by TLS and IR thermography

Caroline Lefeuvre[1,2], Antoine Guérin[2], Dario Carrea[2],
Marc-Henri Derron[2] & Michel Jaboyedoff[2]

[1] Ecole des Mines d'Ales, 6 avenue de Clavières, 30100 Alès, France ; caroline.lefeuvre@unil.ch
[2] Risk Analysis Group, University of Lausanne, Lausanne, Switzerland

Key words: *lidar, thermography, rockfalls, power laws.*

The study area of La Cornalle (Vaud, Switzerland) is a 40 m high south-west facing cliff which is also part of a larger landslide. The cliff is formed by an alternation of marls and sandstones. The thicknesses of sandstone layers range from 0.5 to 4 meters. The rockfall activity of this cliff is high, with almost daily events. The aim of this study is to better understand the links between rockfall activity, cliff structures, and weather and thermal conditions.

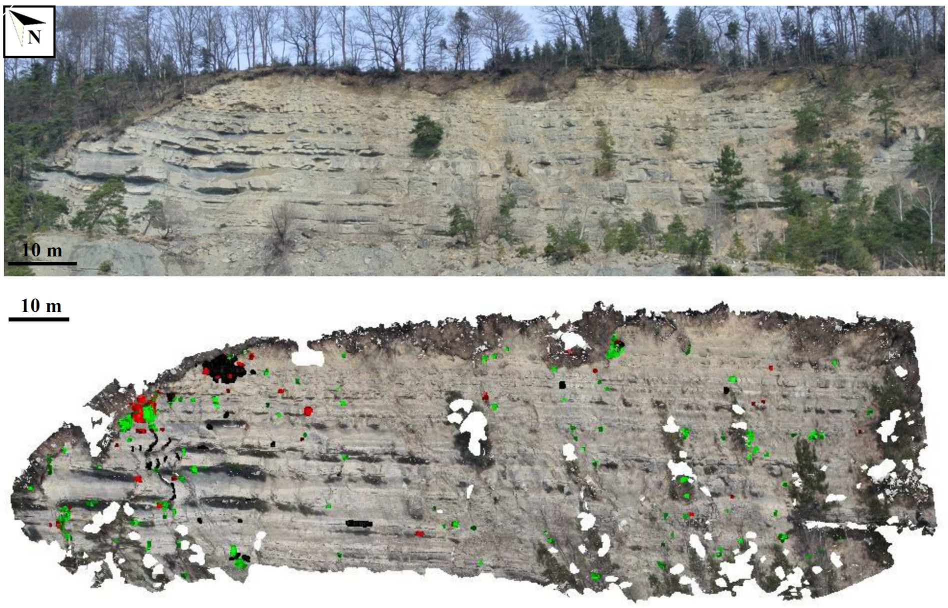


Figure 1. Study area of La Cornalle. Top: Picture of the cliff. Bottom: Fallen blocks between January and April 2016

Figure 1: Study area of La Cornalle. Top: Picture of the cliff. Bottom: Fallen blocks between January and April 2016 detected on terrestrial laser scanning datasets.

120 rockfalls between 01/29/2016 and 02/22/2016
43 rockfalls between 02/22/2016 and 03/18/2016
31 rockfalls between 03/18/2016 and 04/08/2016

The 3D surface evolution of the Cornalle cliff was monitored approximately every month since September 2012 using a terrestrial laser scanning (TLS) in order to get a monthly inventory of rockfall events. A weather station located 150 meters away from the cliff collects data such as temperature, humidity, atmospheric pressure, rain, solar radiation every 15 minutes since November 2013. At the same time a thermic probe was also fixed 10 cm deep in the sandstone and measures temperature every 10 minutes.

To improve the rockfall dating and their relation with rainfall, temperature, freeze and thaw, we placed in March 2015 a camera 275 meters away from the cliff to take three pictures a day. These pictures are compared to event locations detected by TLS to obtain the date of each event.

Power law parameters for rockfall volumes have been estimated from rockfall TLS inventories. The exponent b is very dependent on the considered range of volume. However for intermediate volumes, ranging from about 1 to 40 litres and corresponding to 50-60% of the events for each period, the exponent b is quite stable with a value usually close to 0.3 (Tab. 1).

Period	**Number of event**	**Volume min (m^3)**	**Volume max (m^3)**	**a**	**b**	**R^2**
01/29/2016-02/22/2016	18 (15%)	1.10-5	0.001	83.496	-0.034	0.9171
	76 (63%)	0.001	0.04	9.2505	-0.371	0.9882
	27 (23%)	0.04	1.09	2.3514	-0.748	0.9219
02/22/2016-03/18/2016	12 (28%)	1.10-4	0.002	17.754	-0.102	0.9415
	21 (49%)	0.001	0.02	4.2057	-0.324	0.9711
	14 (33%)	0.02	5.73	1.5715	-0.508	0.8476
03/18/2016-04/08/2016	19 (61%)	1.10-4	0.06	19.4317	-0.173	0.8515
	22 (71%)	0.01	9.37	2.4691	-0.512	0.942
01/29/2016-04/08/2016	27 (14%)	1.10-5	0.001	136.79	-0.034	0.8721
	115 (60%)	0.001	0.04	19.772	-0.329	0.9866
	83 (43%)	0.01	9.37	4.9689	-0.69	0.9735

Table 1. Power law parameters.

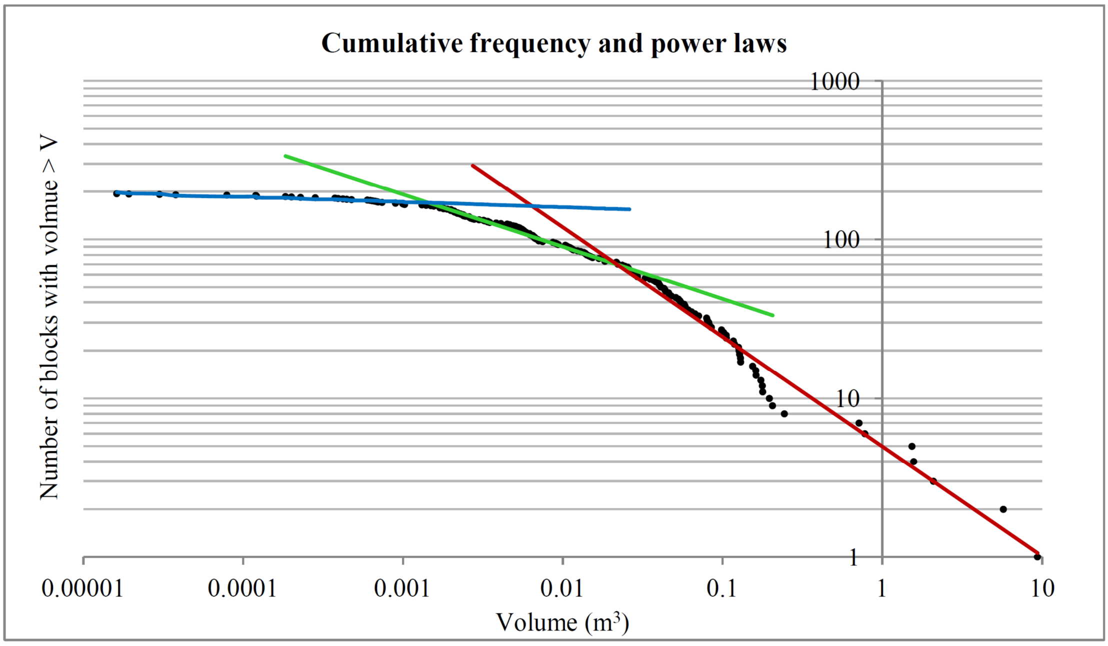


Figure 2: Variations of parameter b in power law scaling of rockfalls.

- *Cumulative frequency between 01/29/2016 and 08/04/2016*
- *Small volumes*
- *Intermediate volumes*
- *Large volumes*

A 3D model of the cliff is developed based on TLS data in order to identify discontinuities, unstable structures and to understand their influence on rockfall events location and frequency. A model of thermal variations, including air temperature, solar radiation, rock temperature and thermal imaging is in development to assess the effect of temperature on unstable blocks and crack opening as demonstrated recently by COLLINS & STOCK (2016).

Reference

COLLINS B.D. & STOCK G.M. 2016. Rockfall triggering by cyclic thermal stressing of exfoliation fractures. *Nature Geoscience*. Published online March 28, 2016. doi: 10.1038/NGEO2686.

Natural neighbour kriging and its potential for quality mapping

Shelley van der Graaf[1], Roderik Lindenbergh[1*] & Edward Verbree[2]

[1] *Faculty of Civil Engineering and Geosciences, P.O. Box 5048, 2628 CN Delft, Netherlands; R.C.Lindenbergh@tudelft.nl*

[2] *Faculty of Architecture and the Built Environment, P.O. Box 5043, 2600 GA Delft, Netherlands;*

Key words: *Natural neighbour, Sibson, kriging, spatial interpolation.*

Spatial interpolation is an essential tool in geosciences. Often a limited number of observations, for example elevation or temperature measurements, are conducted and interpolation is then used to estimate values at unobserved locations. Kriging is a widely used stochastic interpolation method. Kriging calculates the dissimilarities between data pairs and uses this relationship to determine the interpolation weights in such way that the estimation variance is minimized. Kriging estimates are relatively accurate and yield a smaller prediction error than estimates obtained with other interpolation methods. An additional advantage of kriging compared to other methods is that it also gives a quality descriptor, namely the kriging variance. However, kriging requires inversion of matrices and can therefore be a computationally inefficient process when dealing with large datasets. A way to overcome this problem is the use of an interpolation neighbourhood, a selected subset of the input points that are close to the estimation point, rather than using all input points. The interpolation neighbourhood is often defined by an arbitrary number of nearest observations or by a certain region around the estimation point. In this study the use of natural neighbours as interpolation neighbourhood is presented. The natural (or Sibson) neighbours of a certain estimation points are the observations points of which their initial Voronoi tessellation is altered by the introduction of that point. The use of natural neighbours could be a good compromise between the number and spread of input points for kriging. Two case study bathymetry datasets from the North Sea are used to examine the potential of natural neighbour kriging and the suitability of the method for different datasets with distinct signals and configurations. A comparison is made between regular kriging and natural neighbour kriging. The interpolation results are presented in an insightful way, giving information about the contribution of the input points and the distribution of the estimation errors. The most suitable adaptive interpolation grid is proposed based on these quality parameters as well as the input geometry of the data. Natural neighbour kriging is expected to be a useful method for interpolating irregularly spaced datasets. The selection of natural neighbours namely reflects the configuration of the input data, accounting for spatial variations.

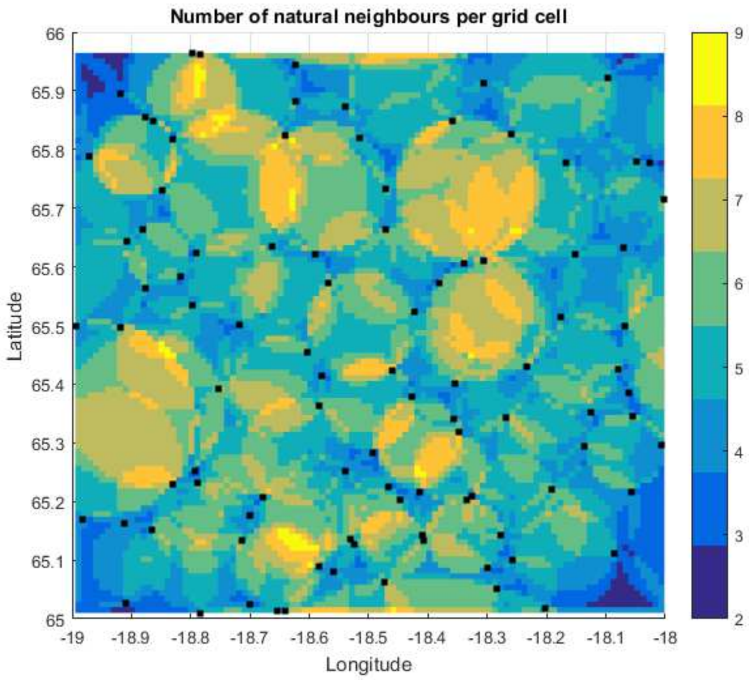


Figure 1: The number of natural neighbours per grid cell that are used as interpolation neighbourhood for kriging, generated for 100 randomly distributed points (black squares).

Virtual analogues of Ypresian carbonated reservoir at Ousselat Cliff (Central Tunisia) using terrestrial laser scanning and GigaPan techniques

Raja Mastouri[1], Antoine Guerin[1], Michel Jaboyedoff[1], Samir Bouaziz[2], Marc-Henri Derron[1], Marzough Lazzez[3] & Achref Boulares[3]

[1] *Institute of Earth Sciences, University of Lausanne, Switzerland, raja.mastouri@unil.ch*
[2] *Engineering School of Sfax, Laboratory "Water, energy Environment", University of Sfax, Tunisia*
[3] *ETAP, " Entreprise Tunisienne d'Activité Pétrolière", Tunisia*

Key words: *virtual outcrop, carbonate reservoir, GigaPan, lidar, Coltop3D, analogue.*

Recently, new developments in 3D high-resolution technology such as terrestrial laser scanning (TLS) and GigaPan provided precise 3D high-resolution data and opened new prospects for structural studies. TLS data of outcrops can also be used to improve reservoir characterization and to integrate other field data (BUCKLEY *et al.*, 2010; HODGETTS, 2013; AGADA *et al.*, 2014).

The outcrop of the Ypresian carbonate at Ousselat (central Tunisia) consists of an important limestone cliff with 130 m thickness affected by fault systems and fracture sets (JORRY *et al.*, 2003). It represents a good marker of tectonic deformation and the main hydrocarbon reservoir in Central Tunisia.

In this study, we used TLS and GigaPans (high-resolution panoramas) to analyse quantitatively and qualitatively fractures of the Ypresian fractured reservoir. We textured the triangular mesh obtained from TLS data with a high-resolution gigapixel panorama thereby creating a photorealistic 3D model (Fig. 1A). This model makes it possible to see details the structures, and thus to calculate the spacing between the fractures at a detailed scale. On the high-resolution panorama obtained with GigaPan, we observed in details the two major faults that build the structures of horsts and grabens (Fig. 1B). I was also possible to map zones with the presence of fossils traces, vuggy and dissolution figures on these data (Fig. 2B).

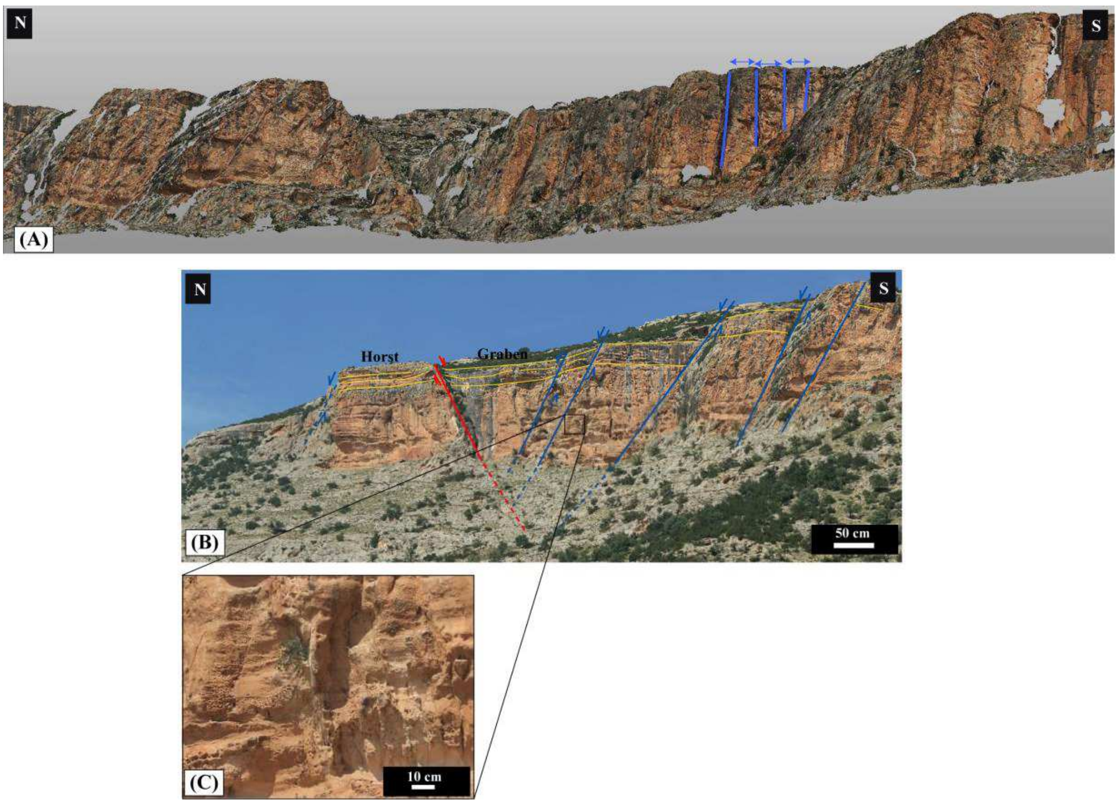


Figure 1: (A) Photorealistic outcrop model of the Ousselat Cliff. (B) gigapixel panoramic of the cliff showing the series of normal faults and (C) the high-resolution detail showing more vuggy and fossils traces.

Coltop3D was used to identify different sets of discontinuities and to measure their orientations. The structural analysis of Ypresian carbonate fractured reservoir shows 5 sets of fractures with different dips and dip directions. They all strike in directions NW-SE, NNE-SSW, NE-SW and ENE-WSW.

Using a photorealistic model, we measured approximately 120 fracture spacings, ranging from 1.75 m to 10 m. The distribution results show that the majority of spacing is characterized by log-normal distributions, except a set which is characterized by a negative exponential distribution. Moreover, coefficient of variation of the Ypresian reservoir ranges from 0.501 to 1, this results show a set fracture is distributed randomly and the other sets are roughly evenly distributed.

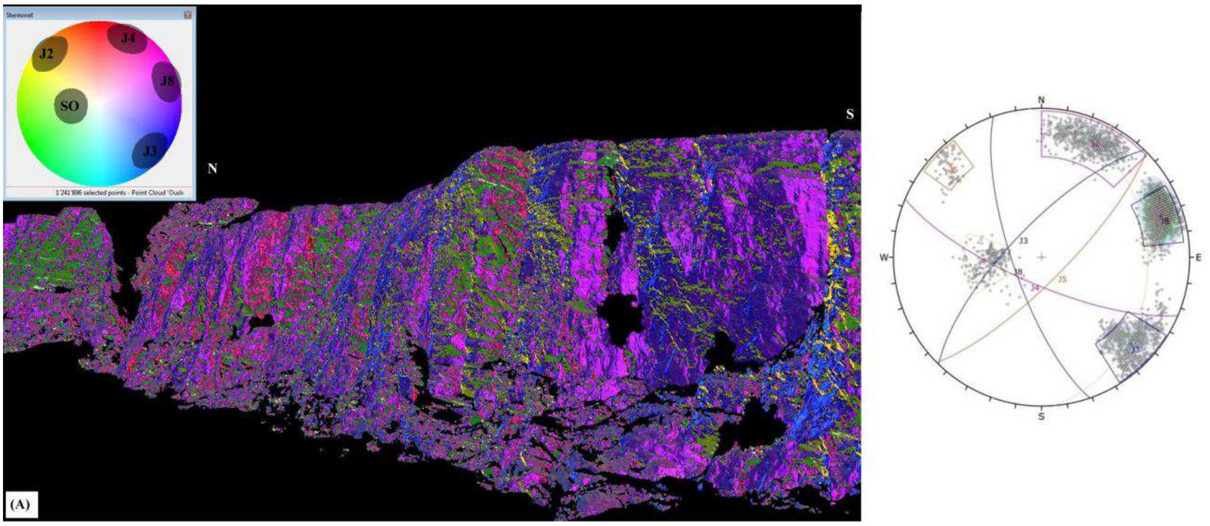


Figure 2: Analysis of fracture orientation of the Ousselat Cliff (Ypresian age). The image on the left shows the 3D view of TLS data displays the fractures orientations detected using Coltop3D. The image on the right shows the stereonet obtained by the point cloud selected.

The results of virtual outcrop are also complemented by fractures observed from the 3D seismic data. The comparison of results obtained from the virtual analogue of Ypresian carbonates reservoir and 3D seismic data shows similarities between the major structures, such as the geometry orientation of faults/fractures and their distributions combining digital outcrop and the seismic data makes possible to reconstruct the fracturing evolution of sedimentary basin from the Upper Cretaceous to the Pliocene. This kind of study is also useful for flow simulation in fractured reservoirs.

References

AGADA S., CHEN F., GEIGER S:, TOIGULOVA G., AGAR S., SHEKHAR R., BENSON G., HEHMYER O., AMOUR F., MUTTI M., CHRIST N., & IMMENHAUSER A., 2014. Numerical simulation of fluid-flow processes in a 3D high-resolution carbonate reservoir analogue. *Petroleum Geoscience,* 20: 125-142.

BUCKLEY, S.J., ENGE, H.D., CARLSSON, C. & HOWELL, J.A., 2010. Terrestrial laser scanning for use in virtual outcrop geology. *Photogrammetric Record*, 25: 225-239.

HODGETTS, D., 2013. Laser scanning and digital outcrop geology in the petroleum industry. *Marine and Petroleum Geology*, 1-20.

JORRY S., DAVAUD E. & CALINE B., 2003. Controls on the distribution of nummulite facies: a case study from the late Ypresian el Garia formation (Kesra Plateau, Central Tunisia). *Journal of Petroleum Geology*, 26(3): 283-306.

Interpretation of compound dune dynamics using imagery and internal structure analysis

Alexandre Medeiros de Carvalho[1], Jean T. Ellis[2], Michel Lamothe[3], Luís Parente Maia[1] & Sérgio Bezerra Lima Júnior[1]

[1] *Instituto de Ciências do Mar-LABOMAR- Universidade Federal do Ceará-UFC- Brazil. Av. da Abolição, 3207 – ZC 60165-081 - Meireles - Fortaleza – CE, Brazil, amcufc@gmail.com*
[2] *Department of Geography and Marine Science Program, Universityof South Carolina, SC, 29208, USA.*
[3] *Université du Quebec à Montreal – Department dês Sciences de la Terre et l' Atmosphere, C.P. 8888. SUCC. CentreVille, Montreal– Quebec, H2X 2J6 Canada.*

Key words: *Bevelled remnant of compound dune, migration direction, panoramic photos, trenches, Ceará State-Brazil.*

This paper aims to analyse dynamic processes of compound dunes based on transport directions of bevelled remnants of barchans/barchanoid migrating on barchanoid dunes. This research was completed along the coast of Ceará State in NE Brazil, just south of the Equator. The coastline of Ceará is 573 km long comprising a headland-bay-beach morphology with sandy beach embayments that serves as a source of sand for the vast inland coastal dunes predominantly WNW direction migration. The tropical climate of Ceará state is characterized by wet and dry seasons, strongly influenced by the displacement of the Intertropical Convergence Zone (ITCZ) that determines the dominant wind and rainfall regime for this region.

We used satellite imagery and panoramic photographs to locate the studied dunes. Imaging on different dates allowed for the monitoring of the dune stretch progress and morphology. Detailed photography was used to analyse the internal structures of the dunes. Aeolian dynamics were inferred by analysing the aeolian internal structures of the dug trenches and their relationship with the surficial morphological features. Trenches were dug to reveal the bevelled remnants of compound dunes along different directions.

The dip angles and directions of aeolian sets were measured using a Brunton compass and an iPhone compass and clinometers. Dip angles were also checked by measurements made directly from the digital photographs. The trenches, interpreted aeolian internal structures, and morphological features were positioned using GPS data. Detailed photos of the sections were taken to register the internal structures for digital analysis.

Large welded and contiguous barchanoid dunes characterize the study area. Most of the dunes are covered by smaller barchanoid and barchans (Fig. 1). The welded compound barchan/barchanoid fields usually cover individual areas exceeding 1000 hectares and measuring more than 7 km wide and 2 km long.

The complex internal structures revealed a set of dip directions ranging from 230-345Az and apparent dips ranging from sub-horizontal to over 34 degrees (Fig. 2). A combination of large barchanoid dunes with small barchanoids/barchans is responsible for the development of migration directions with more than 90° between two different dip directions, although these dunes are from unidirectional wind pattern.

Combining photographic data with measurements of the internal structures indicate that the zigzag crest of the barchanoid migrate, thereby cutting and filling sequences of previous layers are dipping in different directions. Portions of the dune crest can travel further down wind to produce a type of detached dull dune that tends to migrate perpendicular to the main wind direction. This may be related to the partial burial of a dune. During the process, the partially buried dune will have an unobstructed arm that suffer a vortex, influence which encourages the dune arm to migrate toward the centre on the burying dune (Fig. 2). On large compound dunes it is also relatively common for a dune slip face to migrate around the W direction, while simultaneously accompanied by another slip face migrating to the NNW or SSW. These observations are consistent with the observed subsurface structures.

Figure 1: Compound dune. Small barchanoid dunes migrating on the large one with about 300 meters wide and 230 meters long and 30 meters high. Ceará State, Brazil.

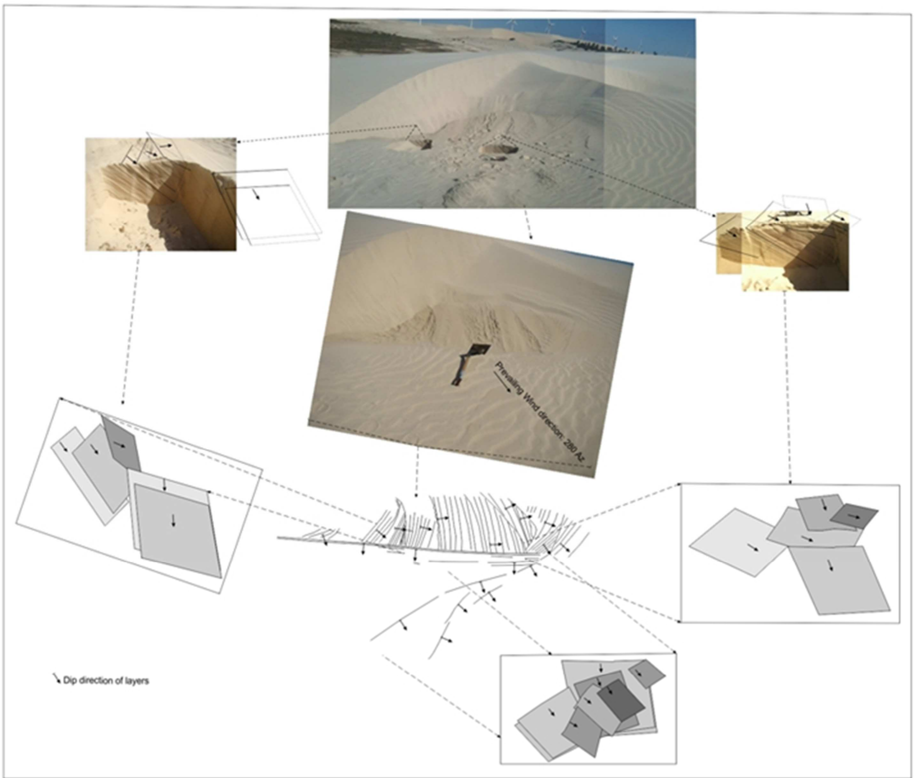


Figure 2: Small barchanoid dune (in the top of photo frame showing aspect of barchan) on large barchanoid. Highlighting a ridge approximately perpendicular to the centre of dune slip face. This crest migrates tending perpendicular to the main direction of the wind. See photo details for migration brands with different directions (on the middle down) and its sections shown in the trenches (on left and right), as well as projections of its layers and dip directions.

Acknowledgements: The authors thank CNPq/Programa Ciências Sem Fronteiras (CsF) for financial support, as well as UQÀM and LABOMAR-UFC for logistical support.

Use of GIS, regional thematic data and site-specific procedures to assess/rank environmental risks at large scale: The Campania region case study

Giulia Minolfi[1*], Stefano Albanese[1], Annamaria Lima[1] & Benedetto De Vivo[1]

[1] *Università di Napoli Federico II, Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Via Mezzocannone 8, 80134 Napoli, Italy; giulia.minolfi@unina.it*

Key words: *environment, pollution, soil, monitoring, risk assessment, digital terrain model.*

Environmental pollution has a crucial impact on the quality of human life. In Italy, after the Legislative Decree 152/2006, the environmental risk assessment has become mandatory for contaminated lands such as brownfields and dismantled industrial activities.

In Campania, a detailed regional geochemical assessment based on concentrations in different materials (air, topsoil, vegetables, human hair) was carried out with the aim of assessing and ranking risks for the local population.

For the purposes of the present study, a total of 3535 topsoil samples have been collected across the whole regional territory based on a grid of 4 km^2 in the urban areas and 16 km^2 in agricultural areas. The concentrations of 52 elements has been determined at ACME Analytical Lab. Ltd (Vancouver, Canada), by means of an Aqua Regia extraction followed by a combination of ICP-MS and ICP-ES methods.

A new approach has been applied to assess/rank environmental risks at regional scale by using geospatial analysis and GIS to translate a European-wide accepted methodology for the preliminary assessment of human health risks at single contaminated sites to a regional scale.

The methodology chosen as a reference for the risk assessment procedures is the PRA.MS (Preliminary risk assessment model for the identification of problem areas for soil contamination in Europe, 2005). Following the PRA.MS guidelines, a conceptual model for the human health risk assessment for the Campania region has been based on four different exposure routes: 1) dispersion of contaminants in groundwater, 2) in surface water, 3) in air, 4) direct contact with the contaminated media (soils). The source, the pathway and the receptor for each of the exposure route are scored on the base of a quantitative or qualitative analysis of some featuring characteristics (parameters).

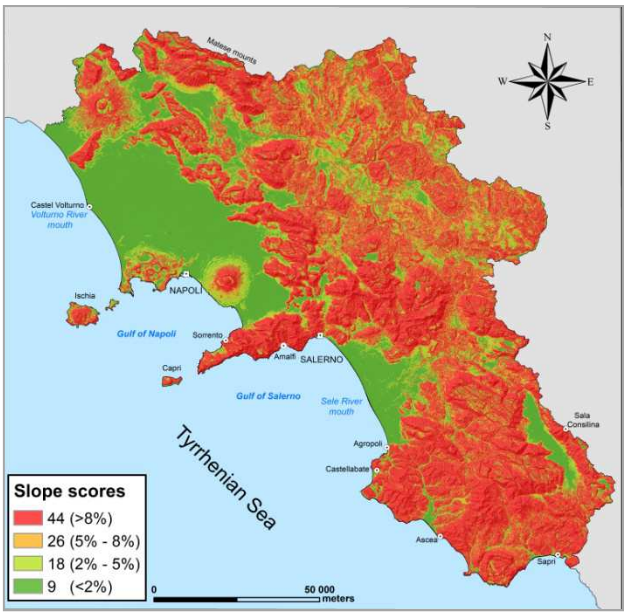


Figure 1: Slope parameter scores map for Campania region, obtained by the DTM 20 m.

A total of 14 representative parameters were chosen, based on the available regional data for Campania. An example is shown in Fig. 1, where the 20 m DTM of Campania region is used to create the slope map, one of the parameters representing the pathway for the dispersion of contaminants in the surface water. The map was reclassified, according to the PRA.MS, in four classes of score, assigning the highest score to the highest gradient of the slope (>8%). Starting from these parameters values, the information is aggregated to higher levels in several steps, adopting a mixed additive and multiplicative algorithm, up to the overall risk score (PRA.MS Application Tier 2, 2006). The final risk map (Fig. 2) is classified according four classes of risk. This map is useful to identify the problem areas, characterized by a higher risk, where more detailed analysis has to be carried out.

The identification of the problem areas is necessary for developing an efficient monitoring system and to produce a ranking of the risky areas to be used as a reference in determining the development of intervention plans, for better addressing the resources dedicated to the environmental remediation of widely contaminated regions.

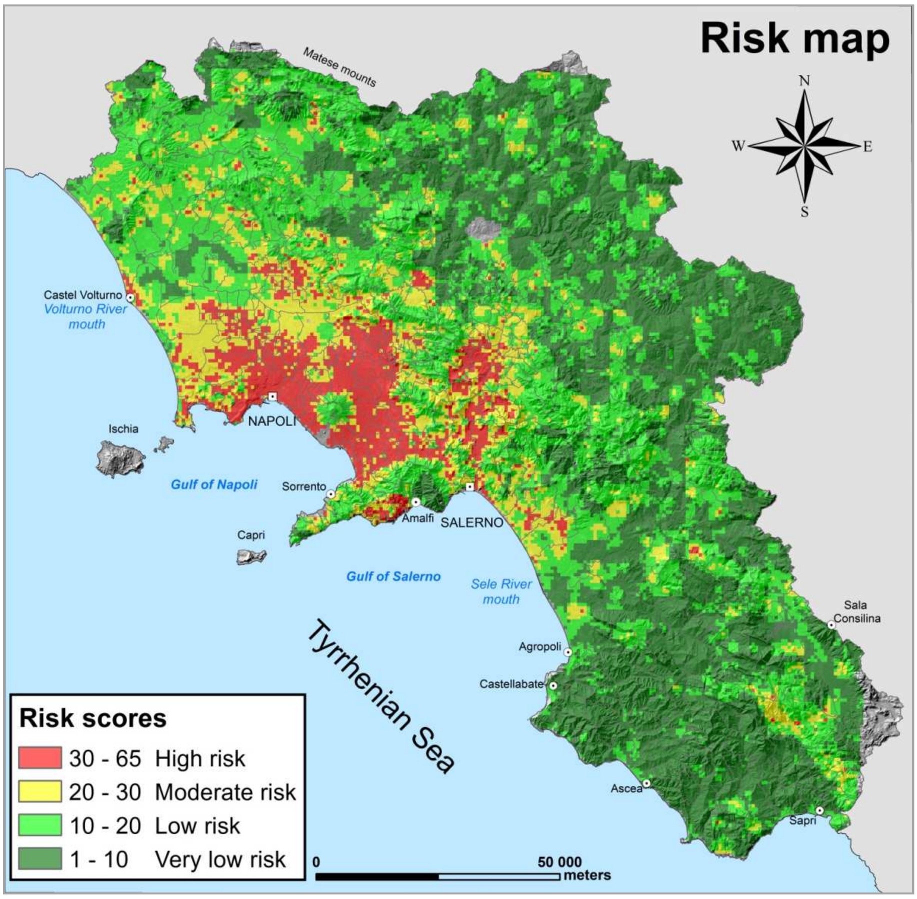


Figure 2: Risk map for Campania region.

References

EEA, European Environment Agency, 2005. Towards an EEA Europe-wide assessment of area under risk for soil contamination. *PRA.MS: scoring model and algorithm*, Volume III.

EEA, European Environment Agency, 2006. Towards an EEA Europe-wide assessment of area under risk for soil contamination. *PRA.MS Application* (Tier 2).

From virtual outcrop models to multiple point statistics training images for improved reservoir modelling

James R. Mullins[1*], John A. Howell[1], Simon J. Buckley[2,3], Christian Kehl[2,3] & Rob L. Gawthorpe[3]

[1] *Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, AB24 3UE, UK; james.mullins@abdn.ac.uk*

[2] *Uni Research CIPR, P.O. Box 7810, N-5020 Bergen, Norway*

[3] *Department of Earth Science, University of Bergen, P.O. Box 7804. N-5020 Bergen, Norway*

Key words: *lidar, photogrammetry, virtual outcrops, reservoir modelling, multiple point statistics.*

Outcrop analogues are well-documented to play a crucial role in resolving facies-scale heterogeneity that is unresolvable at seismic scale, and provide greater 3D geometrical control than well bores (e.g. ALEXANDER, 1993).

Traditional geocellular models are populated by defining the geometry, directionality and size of facies proportions through manually measuring object dimensions and/or variograms from outcrop analogues or ‘borrowed’ from seismic surveys (e.g. SOARES, 1993). Building geologically-realistic reservoir models is limited by the quality of available geological data and the inherent limitations of the modelling algorithm. Variogram-based techniques frequently fail to capture complex geometries, while object-based modelling fails to adequately integrate dense conditioning datasets.

Multiple point statistics (MPS) is a property modelling technique based on representative training image (TI) (STREBELLE, 2002). A TI represents a conceptual numerical description of the geology and should represent all of the expected heterogeneity in the reservoir under study. Geometries and spatial configurations are captured by the statistics of neighbouring nodes rather than the analytical statistics of an experimental variogram. To date the MPS methodology has been hampered by a lack of suitable TIs, and TIs are often produced on a case-by-case basis based on the subjective criteria and experience of the modeller. As MPS simulation is dependent on conceptual training data, constructing representative TIs of the reservoir under study that maintain compatibility with available seismic and core data is a key challenge; especially in 3D. 3D TIs are vital for the construction of MPS realizations demonstrating 3D connectivity.

Recent advances in digital outcrop techniques, such as lidar and photogrammetry, now permit rapid acquisition of high resolution 3D virtual outcrop (VO) models. VO models provide a hugely underused source of quantitative and qualitative information for guiding TI generation, and provide a balance between appropriate subsurface representation and conceptual geological model.

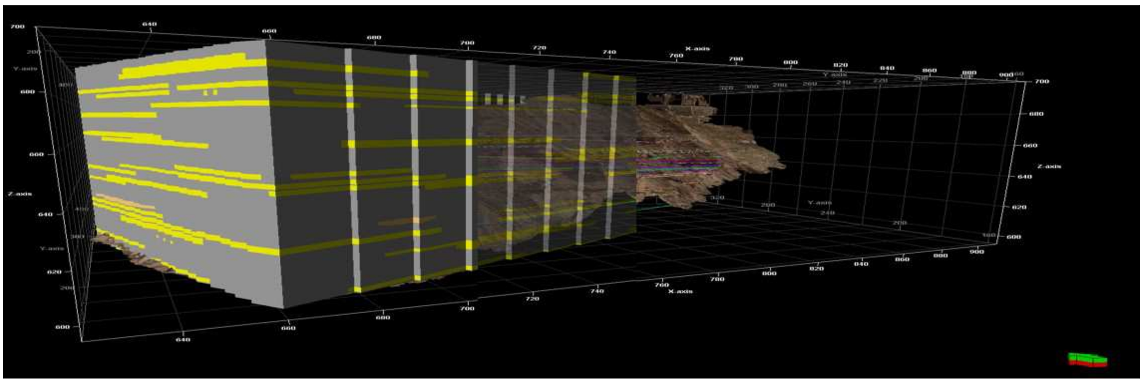


Figure 1: From virtual outcrop to TI for Multiple Point Statistics.

A 149x220x80 metre semi-deterministic static reservoir model of Bolea, Ebro Basin, northern Spain was created to assess a new workflow for deriving TIs from virtual outcrops. The construction of the reservoir model was based on the architectural building blocks of observed sedimentological and structural component from a VO (sensu BELLIAN *et al.*, 2005; ENGE *et al.*, 2007, BUCKLEY *et al.*, 2008). The final facies model was composed of c.1.2 million cells (c. 2.4 million metres^3). With the modelling focus at outcrop and reservoir scale, uncertainty between data densities is minimal and the conceptual static geological model can be transferred directly into a TI for MPS. The TI was used to generate 25 unconditioned MPS realizations to characterise uncertainty while keeping ergodic fluctuations between realizations to a minimum. Realizations were checked visually and using connected bodies and drainable volume to test their validity in comparison to the original TI. Realisations from the TI sufficiently capture and reflect the facies geometries and statistics observed in the original VO and TI respectively. VOs have been shown to have significant potential to guide TI creation.

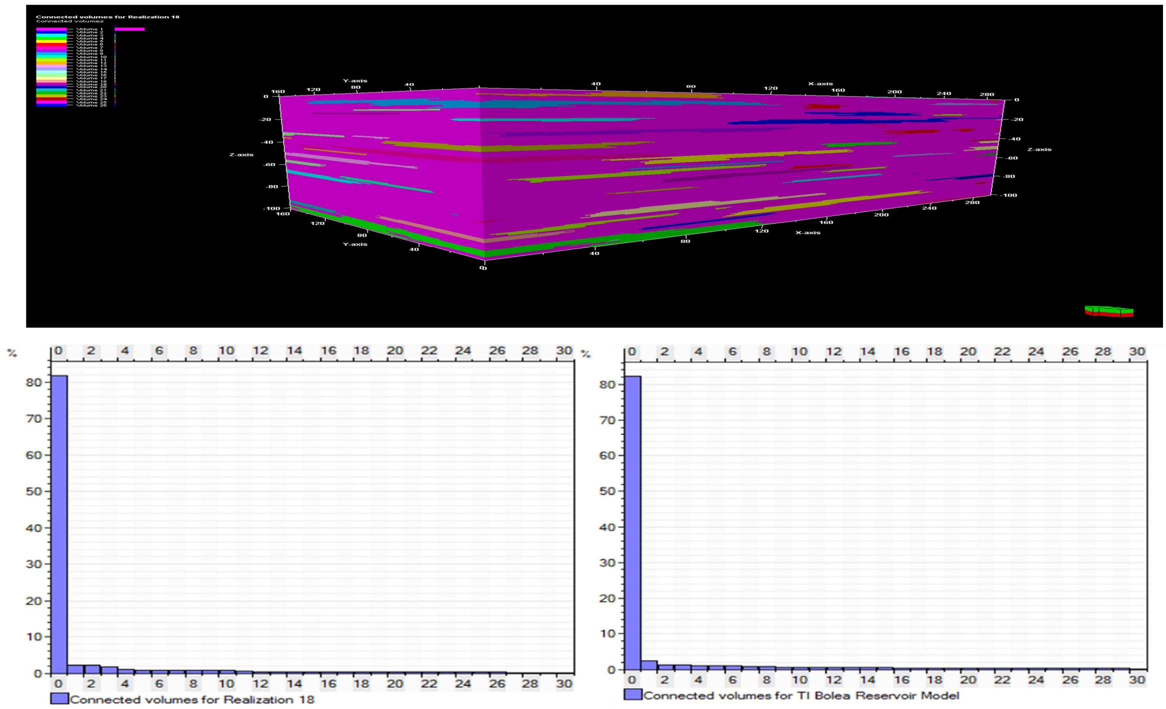


Figure 2: Above: Analysis of connected volumes for one realization. Below: Comparison with TI.

Acknowledgements: This research is part of the ongoing VOM2MPS and SAFARI Phase 3 project sponsored by the FORCE consortium and the Research Council of Norway's (RCN) Petromaks 2 programme (project number 234111/E30).

References

ALEXANDER, J., 1993. A discussion on the use of analogues for reservoir geology. In Aston, M., (eds) Advances in Reservoir Geology. *Geological Society Special Publications*, 69: 175-194.

BELLIAN, J.A., KERANS, C., & JENNETTE, D.C., 2005. Digital outcrop models: applications of terrestrial scanning lidar technology in stratigraphic modelling. *Journal of Sedimentary Research*, 14: 239-256.

BUCKLEY, S.J., HOWELL, J.A., ENGE, H.D., & KURZ, T.H., 2008, Terrestrial laser scanning in geology; data acquisition, processing and accuracy considerations. *Journal of the Geological Society of London*, 165: 625-638.

ENGE, H.D., BUCKLEY. S.J., ROTEVATN. A., & HOWELL. J.A., 2007. From outcrop to reservoir simulation model; workflow and procedures. *Geosphere*, 3: 469-490.

SOARES, A., (eds) 1993. *Geostatistics troia 1992*, 1 & 2: 329.

STREBELLE, S., 2002. Conditional simulation of complex geological structures using multiple-point statistics. *Mathematical Geology*, 34: 1-21.

Automated mapping of discontinuities within Cretaceous dolerite sills, Central Spitsbergen, Arctic Norway

Mark J. Mulrooney[1*] & Kim Senger[1]

[1] *Department of Arctic Geology, University Centre in Svalbard, PO Bo x 156, 9171 Longyearbyen, Norway*
markm1@unis.no

Key words: *photogrammetry, discontinuity mapping.*

We trial software for automated mapping of structural discontinuities in well-jointed Early Cretaceous dolerite sills which intrude the Triassic succession of Central Spitsbergen in the arctic archipelago of Svalbard. The sills are emplaced within an interval currently being investigated as a storage unit for potential CO_2 sequestration (SENGER *et al*., 2014). The study focuses on augmenting or replacing existing manual field based mapping techniques e.g. the line intersection method (SINGHAL & GUPTA, 2010).

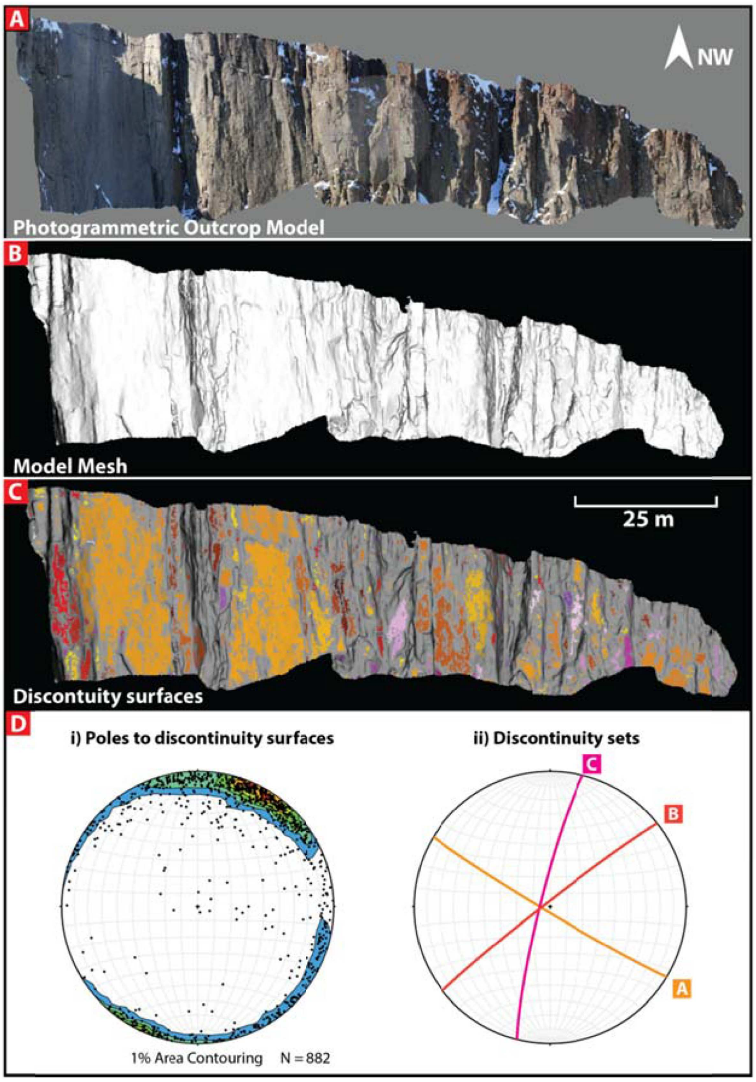


Figure 1: A) Photogrammetric outcrop model off a Cretaceous dolerite Sill intruding the Triassic Succession at Elveneset, Central Spitsbergen, Arctic Norway. B) Smoothened 3D surface model (mesh). C) Discontinuity mapped mesh. D) (i) Poles to 882 discontinuity surfaces with 1% area contouring and (ii) Discontinuity sets identified.

Geo-referenced photogrammetric outcrop models are generated (using Agisoft PhotoScan) from a series of overlapping images acquired with a full-frame DSLR camera with built in GPS unit. The three-dimensional surface model (mesh) is imported into PlaneDetect (VÖGE *et al*., 2013) for automated extraction of discontinuity information. The software, (which was originally developed for engineering geology applications) applies a workflow including; surface smoothing, edge detection and masking, discontinuity identification, and discontinuity set clustering. The software also allows a stereonet of discontinuity orientations coloured by joint set family to be exported, an image of the three-dimensional model with each mapped discontinuity coloured by the set family, and a text file of discontinuity orientations for use in external stereoplot applications.

The automated discontinuity mapping of the Cretaceous dolerite three-dimensional outcrop is summarised in Fig. 1. The study compares the automated method with the traditional 1D line intersection methods i.e. scan lines. Benefits of the automated process include more statistically reliable measurements with significantly reduced directional bias, reduction in time required acquiring data and the ability to remotely collect data from inaccessible areas, especially with the aid of UAV borne cameras. Disadvantages may arise when applied to less well-jointed outcrops, where higher resolution models of smaller areas are required. In addition, non-weathered out discontinues are not measured.

The automated discontinuity mapping method will have huge time saving potential for outcrop based fracture modelling and allow for far greater sample sizes. Further trialling is required in order to determine where the method will fit into future studies, i.e. as a compliment to existing techniques or as a replacement.

References

SENGER, K., PLANKE, S., POLTEAU, S., OGATA, K. & SVENSEN, H., 2014. Sill emplacement and contact metamorphism in a siliciclastic reservoir on Svalbard, Arctic Norway. *Norwegian Journal of Geology*, 94: 155-169.

SINGHAL, B.B.S. & GUPTA, R.P., 2010. *Applied hydrogeology of fractured rocks*. Springer Science & Business Media.

VÖGE, M., LATO, M.J. & DIEDERICHS, M.S., 2013. Automated rockmass discontinuity mapping from 3-dimensional surface data. *Engineering Geology*. 164: 155-162. doi:10.1016/j.enggeo.2013.07.008.

Quantitative mapping of absorption by water, phyllosilicates and sulphate on a geological outcrop

Richard J. Murphy* & Alexander Lowe

Australian Centre for Field Robotics; University of Sydney, NSW, Australia.
richard.murphy@sydney.edu.au

Key words: *hyperspectral, lidar, water absorption, slope stability, minerals.*

Many minerals contain water either as part of their structure (-OH bound to cations) or as unbound water present between the clay sheets or adsorbed onto the surfaces of mineral grains. The wavelength and depth of -OH absorption features provides diagnostic information about mineral chemistry, enabling many minerals to be mapped and quantified on geological outcrops using hyperspectral imagery. Geological outcrops can exhibit variable amounts of moisture caused by sustained seepage of groundwater or the channelling of runoff along certain topographic gradients. The complex interplay between mineralogy and moisture has important implications for the stability of geological outcrops.

Hyperspectral imagery (900-2490 nm) and lidar data were acquired from a road cutting in the Pilbara, Western Australia. The road cutting was characterised by basalt and shale units that had become weathered in places. Hyperspectral imagery was calibrated to reflectance by the empirical line method using calibration standards of different brightness (15% and 60 % Spectralon). High-resolution field reflectance spectrometry (350-2500 nm) identified diagnostic absorptions of kaolinite (2164 nm and 2206 nm), nontronite (2288 nm), Mg-Fe chlorite (2258 nm and 2352 nm) and gypsum (1750 nm and 2210 nm). After the hyperspectral and lidar data were spatially registered, the wavelength position and depth of mineral absorption features were identified from the former using Automated Feature Extraction (MURPHY *et al*., 2014). Gypsum was quantified using ratio of reflectances (1675 / 1750 nm) to quantify the intensity of the absorption caused by sulphate at 1750 nm (Fig. 1). Absorption by water at ~1910-1970 nm was approximated by using a ratio of reflectances (2017 / 1967 nm) at wavelengths on the long-wave slope of this feature that were less impacted by atmospheric absorption (MURPHY, 2015). To minimise effects of noise, the ratio was calculated from a 2nd order polynomial fitted to the reflectance curve between 1961 and 2134 nm. Two maps describing water absorption were created. The first described the total amount of water absorption (i.e. absorption due to water bound in minerals and free water on the surface of the outcrop). The second map described absorption by water for areas of the mine face dominated by minerals that do not contain water as part of their structure (i.e. kaolinite and chlorite). Thus, this second map quantified water absorption caused by increased moisture on the surface of the outcrop.

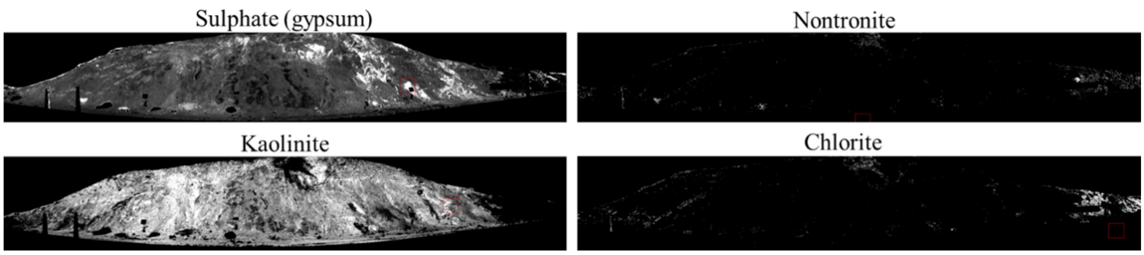


Figure 1: Quantitative mineral maps constructed from the depth (intensity) of the deepest feature in each spectrum.

Absorption features associated with sulphate (gypsum), nontronite, kaolinite and chlorite were successfully identified in the imagery (Fig. 1). Kaolinite was the most abundant mineral and was widely distributed across the outcrop. Mixtures of kaolinite and gypsum were also present. Absorption by water on the outcrop was found to be highly variable (total water absorption is shown in Fig. 2).

Results from this study open up the possibility of using hyperspectral imagery to estimate amounts of water absorption on geological outcrops and partitioning it into maps describing, respectively, free water (unrelated to the mineral structure) and bound water which is present as part of mineral structure.

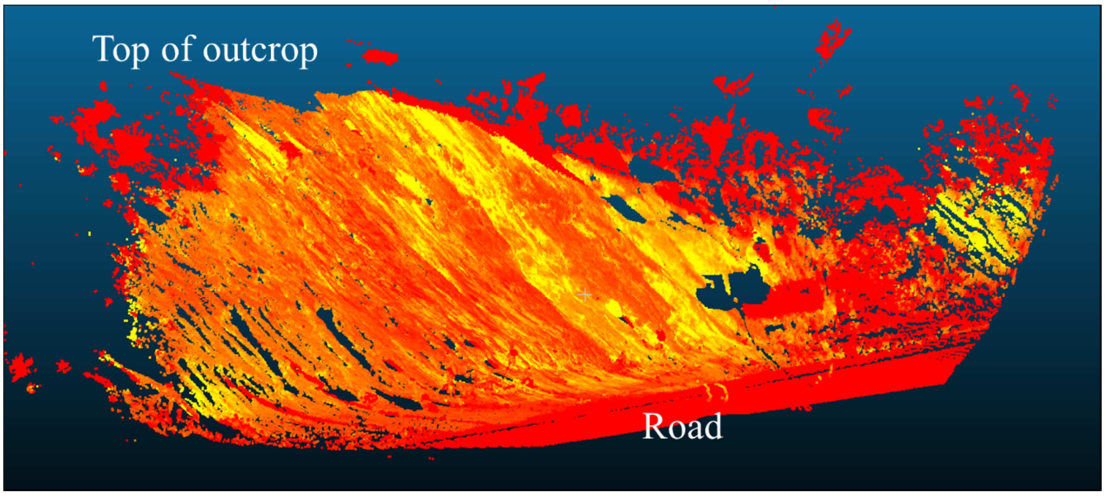


Figure 2: Map of the total absorption by water draped over a lidar point cloud.

References

MURPHY, R.J., 2015. Evaluating simple proxy measures for estimating depth of the ~1900nm water absorption feature from hyperspectral data acquired under natural illumination. *Remote Sensing of Environment*, 166: 22-33.

MURPHY, R.J., SCHNEIDER, S. & MONTEIRO, S.T., 2014. Mapping layers of clay in a vertical geological surface using hyperspectral imagery. Variability in parameters of SWIR absorption features under different conditions of illumination, *Remote Sensing*, 6: 9104-9129.

Insight on the contribution of photogrammetry and UAVs to the mapping and monitoring of unstable rock slopes

Pierrick Nicolet[1*], Martina Böhme[1], Reginald L. Hermanns[1],
Thierry Oppikofer[1] & Ivanna Penna[1]

[1] *Geological Survey of Norway (NGU), Trondheim, Norway; pierrick.nicolet@ngu.no*

Key words: *photogrammetry, UAVs, Rock-slope failure.*

In order to systematically map and to assess the hazard and risk induced by unstable rock slopes in Norway, several remote sensing methods are routinely used, such as airborne and ground-based lidar and satellite and ground-based InSAR. Traditional photogrammetry from airborne pictures taken with calibrated cameras is also sometimes used, but is limited in terms of resolution and acquisition frequency.

To complement these methods, which all have their strengths and limitations, new photogrammetric techniques using consumer-grade cameras seem to be promising. Indeed, numerous pictures can easily be acquired during field study from the ground, from a UAV or from a helicopter. In addition, historic sources might be used, such as old field pictures taken by geologists or publicly available touristic pictures.

Photogrammetric models can be used in the context of rock-slope failures to support the mapping of instability by looking at the geometry in 3D, for the structural characterisation of the rock slope, to build a geometrical model or to measure displacements by comparing two or more models acquired at different time. When it comes to a UAV, apart from the photogrammetric models discussed above, the pictures can help by showing specific features of the instability that are not visible from the ground. In this study, examples taken from different site are presented, looking especially at the site conditions required to build a relevant photogrammetric model and at the model quality.

In the specific context of rock-slope failures, photogrammetry is challenging due to particular conditions. For example, the large dimensions of the features of interest complicate the acquisition. Indeed, pictures taken from the other side of a valley would need to combine long-focal pictures (taken for example using an automatic panoramic head) with short-focal pictures to constrain the blocs. However, the lighting conditions are expected to change during this long procedure, which complicates the construction of a model. In addition, the use of a UAV in such a context is also challenging in that regard. Indeed, multicopter UAVs, which permit pictures to be captured from a relatively stable platform with a non-nadir angle, are limited in horizontal and vertical range, both by their performance and when local laws require a constant visual contact with the UAV. For these reasons, better results have been obtained using pictures taken from helicopter, which is possible in that case since many unstable rock slopes in Norway need to be reached by helicopter anyway.

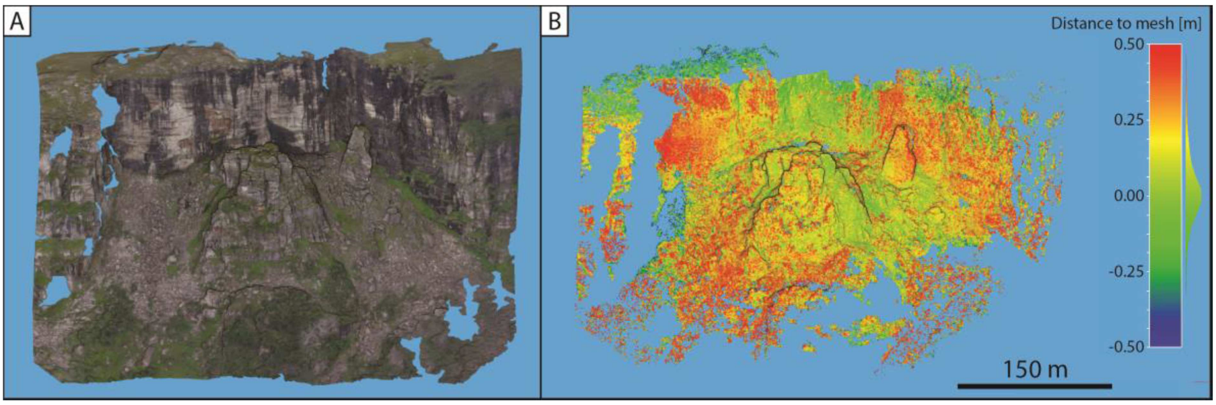


Figure 1: Distance of a point cloud obtained with VisualSFM (B) to a mesh obtained with Agisoft PhotoScan (A). Both models use the same pictures. The mesh has been roughly scaled and oriented using measurements taken in Google Earth, and the point cloud has been aligned to the mesh and scaled using the ICP algorithm implemented in CloudCompare. The relatively large distances from the point cloud to the mesh illustrate the difficulty of measuring millimetric to centimetric displacements.

When it comes to monitoring deformations, the challenge is to detect small changes (millimetric to centimetric) that may occur over large areas (Fig. 1). This requires a particular attention to the model quality and can only be assessed in case of strong local gradients (e.g. deformation localised on a fault plane rather than diffuse deformation). In addition, the presence of vegetation often complicates the analysis and the coreferencing of different point clouds.

The use of old pictures not specifically taken for photogrammetric purposes has proven to be inefficient in most cases. Indeed, the large dimensions of the features of interest needs a systematic approach and unsorted pictures are hardly ever covering the whole area. Furthermore, the combination of field pictures taken on the instability with pictures taken from a distance is generally difficult due to a large baseline. In addition, the sites with a large coverage of publically available touristic pictures is quite uncommon, and, unlike for architectural projects (e.g. SNAVELY *et al*., 2008), the date of the picture is important when it comes to monitoring.

For all these reasons, photogrammetry brings some new possibilities to rock slope instabilities mapping, since a 3D model can easily be obtained and support the mapping, but is still challenging to apply for the monitoring. However, due to the fast developments both in the fields of photogrammetric modelling and UAVs, these tools will certainly bring new possibilities.

Reference

SNAVELY, N., SEITZ, S. & SZELISKI, R., 2008. Modeling the world from internet photo collections. *International Journal of Computer Vision*, 80: 189-210.

Photogrammetric study of fracture surface roughness in shale rocks

Marcin Olkowicz[1*], Marcin Dąbrowski[1] & Piotr Olkiewicz[1]

[1] Polish Geological Institute – National Research Institute, Lower Silesian Branch, Wrocław; molk@pgi.gov.pl

Key words: *photogrammetry, UAVs, Rock-slope failure.*

Accurate models of fracture surface roughness are a key input in modelling of transport in shale gas reservoir. To achieve an expected spatial accuracy of 10 μm, we have developed our own micro-photogrammetric system and a tailored workflow. Important issues that arise during measurements are:

1) Sampling resolution: dense enough sampling is achieved by using a Canon 5DS R 50Mpixel camera with removed effect from the lower pass filter. The ground pixel size is 4.1 μm on objects of a size of 36x24 mm, with magnification 1:1 (real object size: object size on sensor).
2) Depth of field (DOF): due to a very narrow DOF in macro photography (in our case we estimate it to be less than 1 mm), which is mostly related to focal length and distance from photographed objects, to the best of our knowledge, there is no hardware method that allows to take photos with magnification 1:1 and DOF of 2-3 cm. To resolve this difficulty, we use the focus stacking approach, which builds on stitching a set of photos with a moving DOF. We use highly accurate displaceable rail (Cognisys Macro Rail) that allows photos with DOF at different planes to be acquired while the camera is moved with a minimal step of 2 μm.
3) Image distortion: image distortion poses a challenge to photogrammetric reconstruction. We use a Canon EF 100 mm f/2.8L Macro IS USM lens, which is natively characterized by low distortion. Furthermore, we calibrate our system by measuring and then removing distortion from a series of experiments based on imaging regular patterns.
4) Texture features: to increase poor textures of shale rocks we use laser-based Osela Random Pattern Projector to project a pseudorandom dot pattern (23,880 dots) on measured surfaces. Our intention is not only to increase textural features, but also to create stable marker points that are used to build the characteristic point cloud (sparse reconstruction).

The objective of this study is to present micro photogrammetric hardware system based on a camera mounted on a displaceable rail coupled to a pattern projector. We will show how specific routines based on focus stacking are needed to build models with required accuracy and scale. The roughness of reconstructed fracture surface models will be analysed using our own Matlab scripts.

Understanding heterogeneity in aeolian reservoir analogues using virtual outcrop models

Colm Pierce[1*], John Howell[1] & Holger Reike[2]

[1] *University of Aberdeen, Aberdeen UK; c.pierce@abdn.ac.uk*
[2] *DEA, Hamburg, Germany*

Key words: *lidar, reservoir model, UAV, dune, interpretation.*

Geological outcrops have long been used as analogues to understand the geometry and architecture of subsurface hydrocarbon reservoirs. Aeolian (wind-blown sand) reservoirs are understudied in this respect because they are typically considered to be relatively homogenous. However, at deeper burial depths (~5 km) these "tanks of sand" become extremely heterogeneous at a range of scales from the laminae (mm) up to the bedset and system scale (metres to kilometres). Such heterogeneity is controlled by primary facies distributions and bounding surfaces (both related to parent sand dune morphology and migration). This complexity becomes important at depth where relatively subtle facies contrasts are compounded by environment-related and burial-related diagenetic processes which often accentuate rather than overprint primary facies heterogeneities (ELLIS, 1982). Virtual Outcrop (VO) Models have been used in the search for more predictive rules on aeolian facies distribution. VOs have been gathered from four distinctive aeolian systems (spanning a wet to dry climatic continuum) across the Colorado Plateau, USA (Fig. 1). The studied outcrops range from Permian to Jurassic.

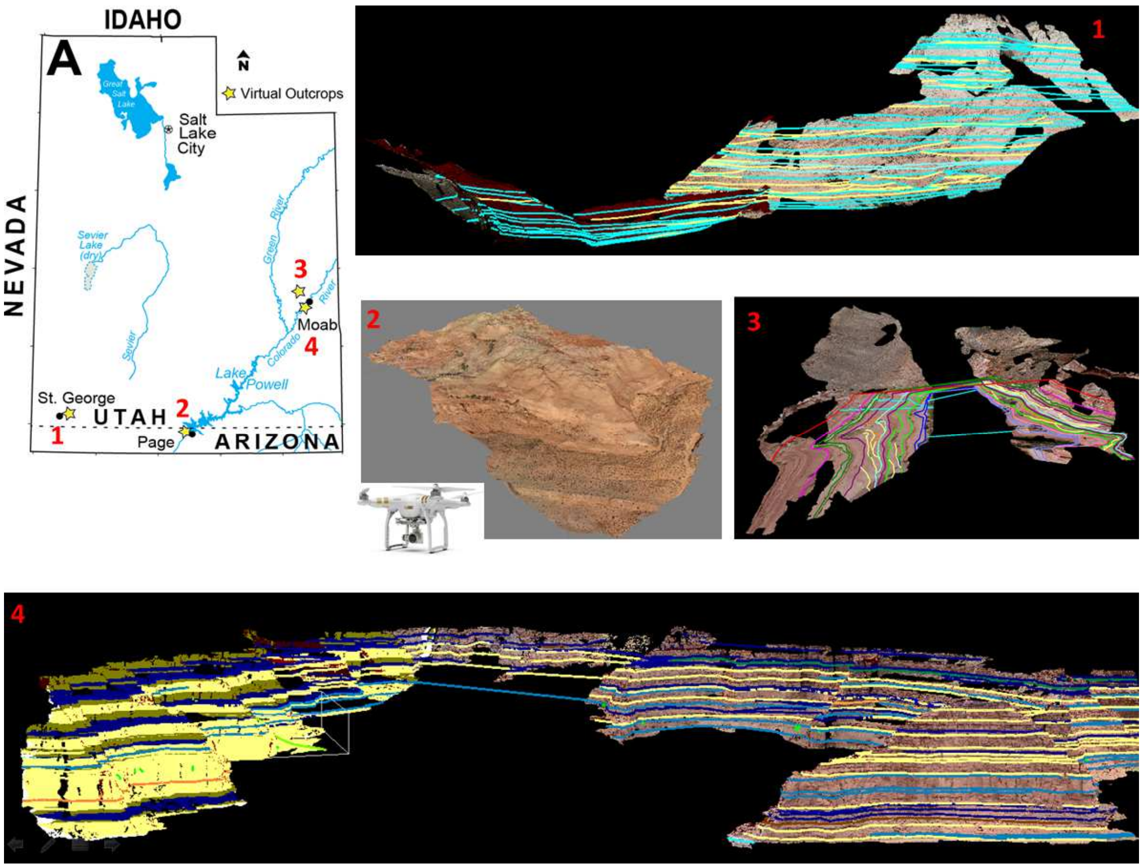


Figure 1: A) Location Map showing virtual outcrop study sites (numbered 1-4) on the Colorado Plateau. The VOs shown are; 1) The Early-Mid Jurassic Navajo Formation (a dry erg system), 2) Mid-Jurassic Page Sandstone Formation (a mixed dry-damp coastal erg setting), 3) The Mid-Jurassic Entrada Formation (damp-wet coastal erg) and 4) The Permian undivided Cutler Group (mixed fluvial and wet ephemeral dune system).

Each locality has been selected to provide the maximum degree of 3D exposure (i.e. avoiding simple straight vertical cliff acquisitions) making them ideal for investigating large scale aeolian bedform architecture. The digital outcrop models were gathered using terrestrial lidar combined with ground based and in some cases UAV (drone) acquired images. The models range in scale from c. 0.3 to 1.2 km^2 in area.

In each case the VO is supplemented by traditional field data including graphic logs, petrophysical sampling and laminae scale measurements. The synthesis (Fig. 2) of this multiscale investigative approach has allowed the rapid assembly of a large volume of quantitative data spanning foreset to system scale. The abundance of quantitative data allows for more accurate reconstruction of parent dune geometries and hence revised depositional models. These models in turn allow for a more detailed reconstruction of facies distribution in 3D away from the outcrop control points.

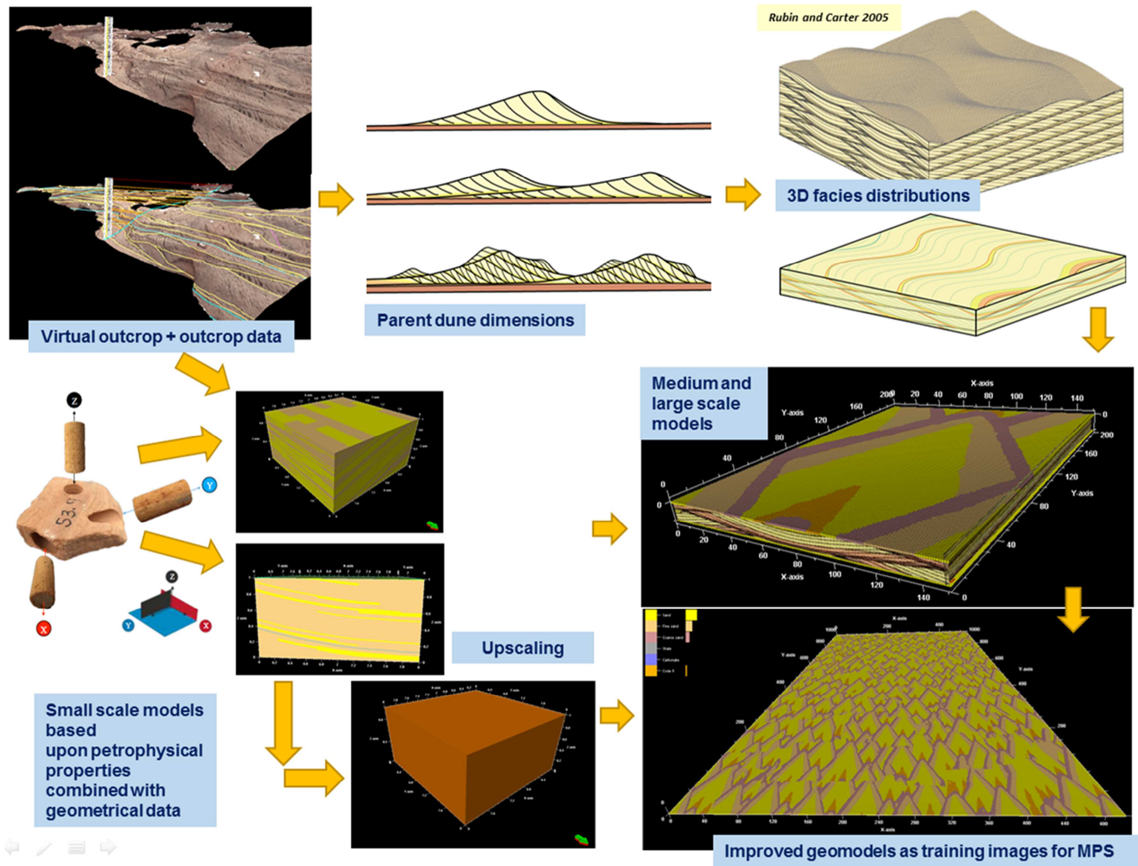


Figure 2: Workflow diagram showing the initial data collection combining outcrop samples, graphic logs and virtual outcrop moving towards modelling of the interpreted parent dune morphology and finally representative geomodels at various scales conditioned from the available outcrop sections.

Geocellular models have been built at the micro (facies), meso (bedform) and macro (system) scales (Fig. 2). These were conditioned in each case from the field data and a revised depositional model. The meso-scale models were produced using a combined methodology of three-dimensional quantitative, bedform forward modelling software (after RUBIN & CARTER, 2005) to produce training images for multi-point statistics. The models were then be populated with the petrophysical data and used to determine Representative Elemental Volumes for the different scales of heterogeneity within the system.

References

ELLIS, D., 1993. The Rough gas field: Distribution of Permian aeolian and non-aeolian reservoir facies and their impact on field development, in C. P. North and D. J. Prosser, eds., Characterisation of fluvial and aeolian reservoirs: *Geological Society London Special Publication*, 73: 265–277.

RUBIN, D.M. & CARTER, C, 2005. Bedforms 4.0: MATLAB code for simulating bedforms and cross-bedding. *U.S. Geological Survey Open-File Report 2005-1272*: 13.

Observing ground deformation phenomena: High resolution topography data from remote to proximal sensing

Luca Pizzimenti[1*], Riccardo Civico[1], Carlo A. Brunori[1], Stefano Pucci[1], Paolo M. De Martini[1] & Daniela Pantosti[1]

[1] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica, Via di Vigna Murata, 605 – 00143 Roma, Italia; luca.pizzimenti@ingv.it*

Key words: *lidar, photogrammetry, UAVs, laser scanning, DTMs.*

We present the activities of the INGV High Resolution Topography Lab, focussed on the use of high-resolution topography (HRT) from different sources (airborne lidar scanning; ALS, terrestrial laser scanning; TLS, and structure from motion photogrammetry; SfM) to support the study of landscape evolution and natural hazards.

As a first case study, we present the preliminary results of a workflow consisting of SfM photogrammetry from low-altitude (Fig. 1), low-cost aerial platforms (helikite, motor paraglider and unmanned aerial vehicles; UAVs) coupled with TLS, aimed at obtaining multi-temporal and high-resolution digital topography datasets of selected active faults in the Central Apennines (Italy). These data are of critical importance to: 1) enable a fine-scale identification and mapping of fault geometry and displaced geologic/geomorphic markers, supporting active tectonic and paleoseismic research; 2) monitor exposed bedrock fault planes for the quantitative analyses of near-fault shaping due to surface processes, useful for the validation of techniques that estimates slip-rate and paleoseismological record on active faults on the base of cosmogenic exposure dating methods (SCHLAGENHAUF *et al*., 2011); 3) obtain pre-earthquake imagery necessary to determine near-fault ground deformation after a future surface-rupturing earthquake; and 4) allow post-earthquake documentation of surface ruptures.

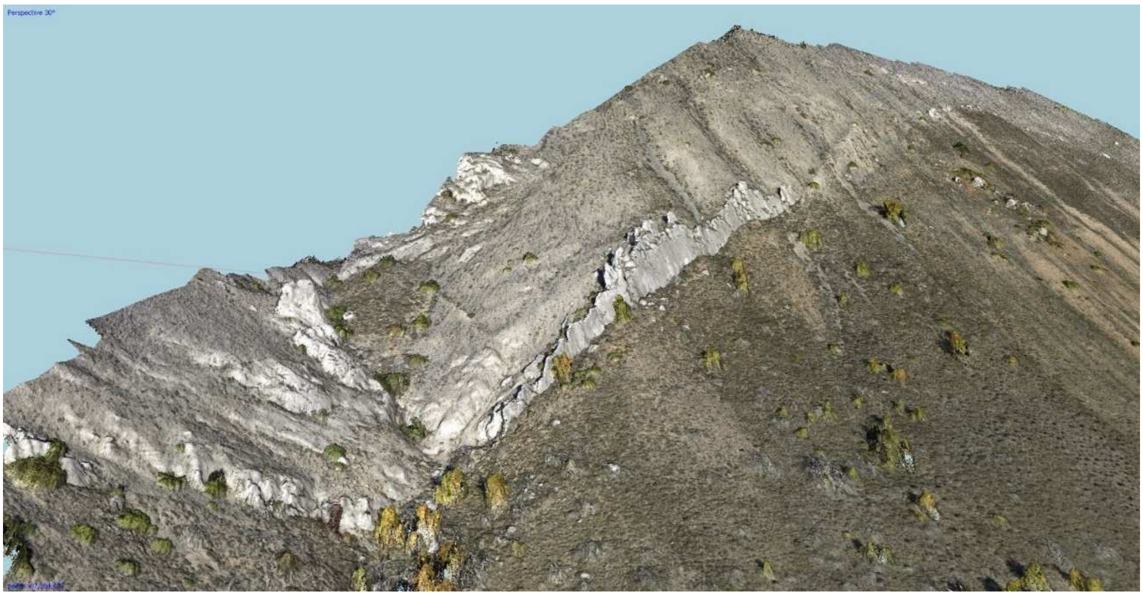


Figure 1: SfM-derived dense cloud acquired from a helikite: a portion of the Roccapreturo bedrock fault plane (Central Italy).

Furthermore, the use of ALS-derived bare earth DTMs allowed an improved identification and characterization of geomorphic markers. As a second case study, we present a revised mapping and classification of the marine terraces in the Capo Vaticano area (Calabria - Southern Italy), on the basis of the work of CUCCI & TERTULLIANI (2006).

In addition, ALS data are critical to produce accurate inundation maps for different sea-level rise scenarios. Here we present a preliminary assessment of the impact of sea-level rise for a densely populated and highly urbanized area SW of Rome (Fig. 2), where important infrastructures and lifelines are located.

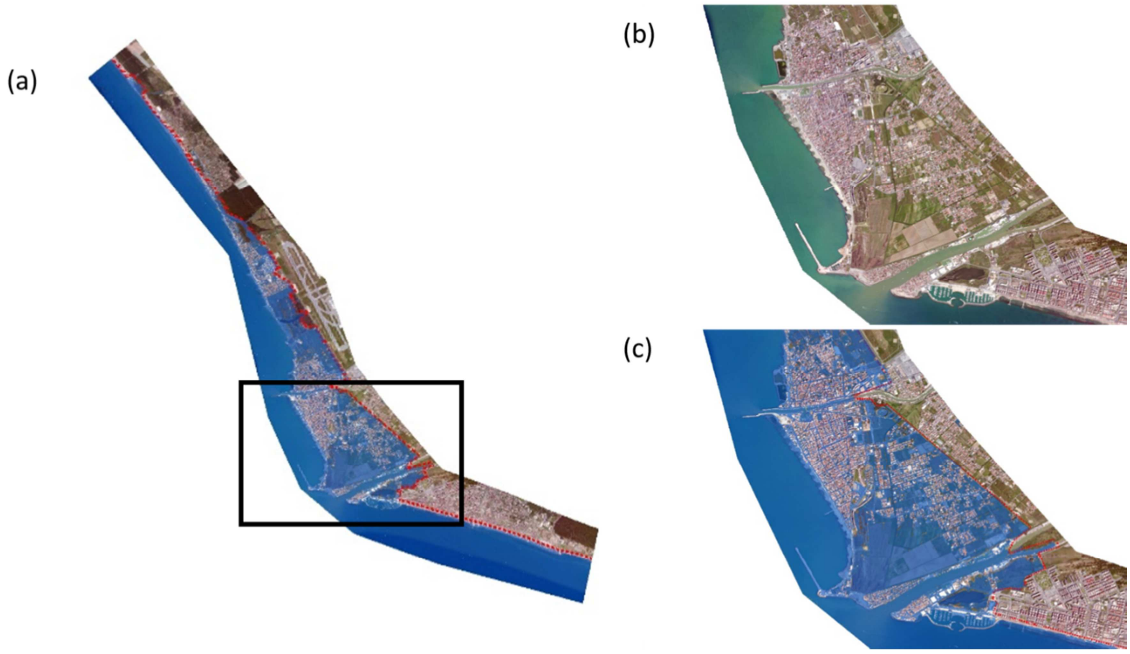


Figure 2: Sea level rise model on low – gradient coastal area: (a) the Fiumicino coastal area (the dashed red line defines the maximum flooding distance for a sea-level rise of 2 meters); (b) and (c) represent Fiumicino town (Black box in (a)) before and after the flooding).

References

CUCCI, L. & TERTULLIANI, A., 2006. Marine terraces in the area of Capo Vaticano (Calabrian arc): Only records of regional uplift or also a clue of coseismic deformation?) (In Italian). *Italian Journal of Quaternary Sciences*, 19(1): 89-101.

SCHLAGENHAUF, A., MANIGHETTI, I., BENEDETTI, L., GAUDEMER, Y., FINKEL, R., MALAVIEILLE, J. & POU, K., 2011. Earthquake supercycles in central Italy, inferred from 36Cl exposure dating. *Earth Planet. Sci. Lett.*, 307: 487-500.

Repeated boat-borne lidar survey to quantify coastal erosion in Carry-le-Rouet (Southern France)

Melody Prémaillon[1*], Thomas Dewez[2], Jérémy Giuliano[3] & Nathalie Marçot[2]

[1] *GET, Université de Toulouse, UPS (OMP), CNRS, IRD, 14 avenue E. Belin, 31400 Toulouse, France*
[2] *BRGM, Risks and Prevention direction, 45060 Orléans and PACA territorial direction, Marseille 13009, France*
[3] *Université Nice Sophia Antipolis, CNRS (UMR 7329), observatoire de la côte d'Azur, GéoAzur, Valbone 06260, France*

Key words: *lidar, geomorphology, coast.*

The Mediterranean coasts of Provence-Alpes-Cote-d'Azur (southern France) are bounded by several hundreds of kilometres of cliffs. Yet, despite urban expansion along cliff edges, cliff collapses hazard have so far received very little attention from scientists. Even local average recession rates are currently unconstrained. To quantify cliff collapse hazard, laser scanning has established itself as a reference tool in the last decade. But the vertical face of the cliffs precludes quantification from standard airborne lidar scanning, and the absence of exposed coastal platform, because the micro-tidal regime does not expose platforms at low tide, precludes conventional terrestrial laser scanning. Instead, the emergence of mobile laser scanners aboard a boat appeared as a potential option to quantify relief changes. This presentation thus describes (i) the use of a boat-borne mobile lidar system over a stretch of coastline a few kilometres long; (ii) explicit quantification of point cloud change detection thresholds; (iii) the projection technique used to flatten a sinuous cliff face with a set of mathematically developable surfaces; and (iv) geomorphological significance of detected changes.

Three surveys were performed by two different sub-contractors, in February 2011, December 2011 and July 2012 along the 3.5 km-long cliff of Carry-le-Rouet (15 km west of Marseille) (Fig. 1). Laser point spacing was improved over time: 1 pt/10 cm, 1 pt/9 cm and 1 pt/6 cm. A high point cloud density was achieved by passing multiple times in front of the cliff and navigating as closely to the cliff as safety allowed.

To quantify geometric precision, five static homogeneous areas, 9 m² to 22.5 m², were used, i.e. planar walls located above the cliff face. These walls, geometrically modelled as best-fitting planes, served to characterize the internal point cloud precision on a statistically relevant point samples n>1000 pts. It revealed the internal multi-pass registration quality, survey positional accuracy and the inter-epoch topographic change detection threshold. Change detection was quantified as the, very restrictive, 99.9% percentile of points-to-best-fitting-planes. Rock scars were thus considered detected when cloud-to-cloud distances were larger than 17.9 cm (epochs 2 to 1), 13.4 cm (epochs 3 to 1), 13.2 cm (epoch 3 to 2) over patches of 10 cm x 10 cm in size (GIULIANO *et al.*, submitted).

The planform geometry of Carry-le-Rouet cliffs has a sinuosity of ca. 1.6 (4.51 km coastal length over 2.82 km in straight line (Fig. 1a). Sinuosity voided the usual assumption of cliff planarity and complicated matters for interpreting point clouds and results. A projection was designed to transform the 3D cliff face into mathematically developable 2D figures made of contiguous vertical planes and cylinder arcs (Giuliano *et al.*, submitted).

The average erosion rate of the Carry-le-Rouet cliffs comes as 8 mm yr^{-1}. In detail, a rock fall scar inventory counted 14900 erosion patches with volumes spanning four orders of magnitude, from 2.8×10^{-3} m^3 up to 65 m^3. Eroded blocks are mainly thick, 21 cm on average, which we interpret to reflect cliff fracturing. When normalized for surface area, "marl and sand" layers (Miocene) (Fig. 1b) are three time more sensitive to erosion than conglomerates or limestone layers. Erosion was mostly focused in the lower part of the cliff (Fig. 1c), with a maximum of erosion exceeding 15 mm yr^{-1} at 3-4 m above NGF-69 datum. This maximum of erosion at low elevation suggests perhaps that erosion reflects stronger marine processes than subaerial ones during the investigated time span.

From the rock fall scar inventory, an empirical negative power law was adjusted to relate rock fall scar volume to annual frequency: F = a V-b, with F being the expected annual frequency per kilometre of cliff, V the volume of a block The empirical exponent b fitting the power-law function came out to be somewhat superior to 1, which is highly unusual for rock fall hazards known elsewhere. Such high b value means that far more small events occurred during that time span than larger rock falls. For now, we attribute this observation to the short span of the study which may have sampled too little rock falls with volumes larger than 10 m^3. Overall, rock fall hazard is quite low with only one event bigger than 10 m^3 expected per year and per cliff kilometres. This is nevertheless compatible with field observations where the largest known event on the commune occurred in 2008 and had a volume of the order of 500 m^3.

Finally, because boat-borne laser scanning is an expensive survey solution that requires the convergence of narrow navigation conditions on top of bringing together many different technologies, each prone to failure in its own way, we computed the empirical surface-volume relationship enabling to convert the probability distribution function of rock fall scar areas into a probability distribution function of volumes. The relationship also takes the form of a power law: $V = a S^b$ with V being the volume of the eroded block and S its surface area. a = -0.64; b = 1.06. In this way, sets of scaled photographs can be used to measure the area of rock fall scars at a given time and infer the volume distribution. This is a means to easily access coastal hazard information without expensive full-3D lidar survey

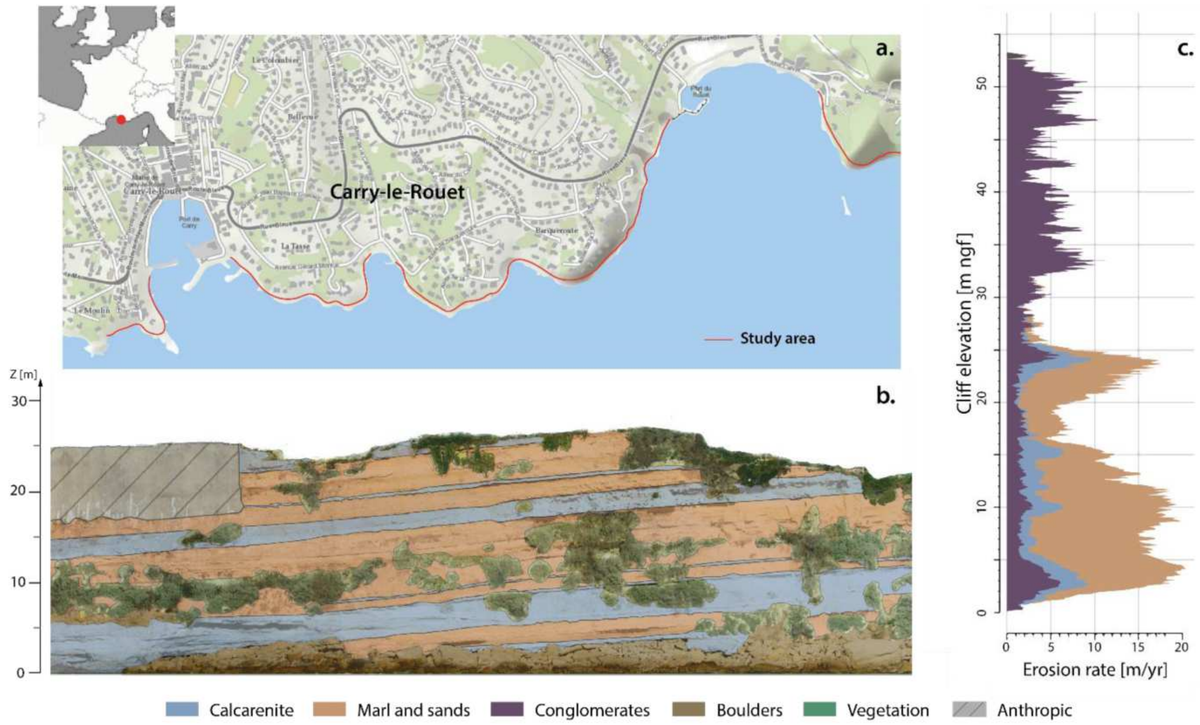


Figure 1: Case study of Carry le Rouet where repeated boat-borne laser scanning surveys took place between February 2010 and July 2012. a. Localisation of study site, note the sinuosity of the coastline; b. Cliff section orthophoto interpreted for lithology; c. Erosion rate profile for cliff elevation with the proportion for each lithology. Erosion is focused on the lower half of the cliff with a maximum at 3-4m above NGF69 datum. Marls and sands layers are most prone to erosion.

Reference

GIULIANO, J., DEWEZ, T.J.B., LEBOURG, T., GODARD, V., MARÇOT, N. & PRÉMAILLON, M., submitted. Mapping coastal erosion of a Mediterranean cliff with a boat-borne laser scanner: performance, processing and cliff collapse hazard. *Engineering Geology*.

From photorealistic outcrop models to synthetic seismic images

Kari Ringdal[1], Simon J. Buckley[1,2*], Isabelle Lecomte[2,3,4], Ingrid M. Anell[4] & Alvar Braathen[4]

[1] *Uni Research CIPR, P.O. Box 7810, N-5020 Bergen, Norway; simon.buckley@uni.no*
[2] *Department of Earth Science, University of Bergen, P.O. Box 7803, N-5020 Bergen, Norway*
[3] *NORSAR, P.O. Box 53, N-2027 Kjeller, Norway*
[4] *Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, N-0316 Oslo, Norway*

Key words: *photogrammetry, modelling, geophysics, outcrop, interpretation, visualisation.*

Digital modelling of geological outcrops has become widely used over the last decade, due in part to advances in data collection hardware and processing software, which have resulted in greater accessibility to a wider range of geoscientists. Digital outcrop models provide the spatial framework for linking the topographic representation with other application data, such as field photos, panels and logs, and serve as the basis for interpretation and quantitative analysis. However, an important area of ongoing research is how 3D spatial can be integrated with other imaging sources, such as multispectral and hyperspectral imaging, thermal imaging and terrestrial radar interferometry. Furthermore, incorporating geophysical data with high resolution spatial data allows the bridge between 2.5D (topographic surface modelling) to full 3D (internal structures) to be realised, aiding understanding of the subsurface and the resolution gap between digital spatial mapping data and lower resolution seismic methods.

In this contribution, we present a workflow for generating synthetic seismic images from seismic-scale digital outcrop models, as well as novel visualisations to allow geoscientists to appreciate how outcrops and geological features can appear in real-world subsurface settings. The base digital outcrop model is used as the framework for interpreting geological structures and facies using polylines and polygons to define zones. These are then projected as a texture to an orthorectified plane, and used as input to ray traced seismic modelling (LECOMTE *et al*., 2015). Interpreted zones are given seismic and rock properties based on analogous facies in the subsurface (e.g. HODGETTS & HOWELL, 2000), which can be easily varied to allow different seismic imaging scenarios to be assessed. The generated synthetic imagery is imported back onto the projection plane in the digital outcrop interpretation environment for comparison purposes. Finally, the synthetic seismic image is overlain as a new texture layer onto the digital outcrop model, with spatial position matching the original interpretation. Graphical blending of the modelled seismic texture layer (BUCKLEY *et al*., 2013) permits geoscientists to easily appreciate how geological features are represented as parameters such as velocities, model depth and ray angles are varied. A case study is presented from Edgeøya, Svalbard.

Acknowledgements: The authors acknowledge an internal grant award from Uni Research CIPR for developments made to the LIME software during this research project. Aspects of this work have been funded by the Research Council of Norway and Tullow Oil Norge, Lundin Norway, Statoil Petroleum, Edison Norge and Dea Norge through the Petromaks 2 programme (Trias North, project number 234152).

References

BUCKLEY, S.J., KURZ, T.H., HOWELL, J.A. & SCHNEIDER, D., 2013. Terrestrial lidar and hyperspectral data fusion products for geological outcrop analysis. *Computers & Geosciences*, 54: 249-258.

HODGETTS, D. & HOWELL, J.A., 2000. Synthetic seismic modelling of a large-scale geological cross-section from the Book Cliffs, Utah, USA. *Petroleum Geoscience*, 6: 221-229.

LECOMTE, I., LAVADERA, P.L., ANELL, I.M., BUCKLEY, S.J., SCHMID, D.W. & HEEREMANS, M., 2015. Ray-based seismic modeling of geologic models: Understanding and analyzing seismic images efficiently. *Interpretation*, 3(4): SAC71-SAC89.

High resolution glacier monitoring over Nigardsbreen, Norway, using a GoPro camera and an acrobatic plane

Benjamin Aubrey Robson[1*], Christopher Nuth[2], Luc Girod[2], Liss Andreassen[3] & Svein Olaf Dahl[1]

[1] *Department of Geography, University of Bergen, Fosswinkelsgate 6, 5015 Bergen, Norway*
[2] *Department of Geoscience, University of Oslo, Norway*
[3] *Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway*

Key words: *glacier, structure from motion, DEM, Norway.*

High resolution digital elevation models (DEMs) are needed for many applications within glaciology, such as change detection, modelling and the estimation of water resources. Current methods used for data capture (such as lidar) are however in most cases prohibitively expensive. Given the rapid rates of glacier melting over the previous decades, data can quickly become out of date. Advances in computer power and image processing techniques have allowed structure from motion (SfM) techniques to be used to generate DEMs from overlapping imagery. Here, we show the workflow and preliminary results from a flight over Nigardsbreen in Norway where a GoPro camera was used to collect many hundreds of overlapping photos and generate a high resolution (sub-metre resolution DEM). The results are compared with a 2013 lidar campaign. Over exposed ice, sufficient contrast was available for a high level of image matching; however on snow covered terrain it was not possible to match images. We therefore recommend such mapping as a relatively low-cost method of glacier volume change monitoring for the ablation area of ice masses.

Photogrammetry with DJI Phantom 2 drone: 3D model of an area deformed by neotectonics in the Venezuelan Andes

Riccardo Rocca

Repsol, Madrid and drone enthusiast;
riccardo.rocca@hotmail.com

Key words: *photogrammetry, geoscience, Venezuelan Andes, neotectonics, DJI, Phantom.*

This presentation describes an experience of mapping a geological feature in the Venezuelan Andes with a DJI Phantom 2 Vision Plus drone.

The Venezuelan Andes are characterized by the presence of a major lineament, the Boconó strike-slip fault that intersects geomorphic features modelled by the latest glaciation. This fault is oriented SW-NE and extends more than 300 km. Its motion has displaced various landscape features that cross the fault, in particularly the "Los Zerpa" moraine system, located a few km NE of the locality "Apartaderos". This moraine formed during the last glaciation that ended 16,000 years ago; its northern tip crosses the Boconó fault and is displaced 100 m towards NE; this corresponds to a rate of movement of 6 mm/year, which is consistent with GPS measurements.

An area of 400 by 600 m was covered over the moraine system, acquiring a total of about 300 images with a DJI Phantom 2 Vision Plus drone, with two flights of 20 minutes each. The images were processed with Pix4Dmapper software, generating a merged georeferenced map and a 3D digital model.

The analysis of the 3D digital model has permitted to clearly identify various geomorphic features related to the interaction between the Boconó fault and the moraine deposits:

- Tectonic scarps identifying the fault trace;
- A 90º sharp bend of the stream running down the glacial valley, where it gets deviated along the fault strike;
- The 100 m dextral displacement of the lateral moraines and glacial valley as they cross the fault;
- Two terraces witnessing past periods of fluvial infill within the glacial valley, later eroded when the fault activity opened a fluvial escape through the right lateral moraine;
- The abandoned fluvial valley that used to drain the moraine system before it was breached by the fault.

The 3D model has allowed representing geological concepts that were described in literature in the past, in particular:

- The geometry of the fault trace, marked by the drainage pattern and tectonic scarps, and its strike slip movement;
- The drainage evolution, through phases when the glacial valley was filled with sediments and later breached by the fault activity, with subsequent erosion of the previous deposits.

In conclusion this experience has proven the benefit of using this technology in geological fieldwork. Having represented the area of interest as a digital model, has allowed testing geological concepts in three dimensions in a much more effective way than with the classic representations of two dimensional maps and sections.

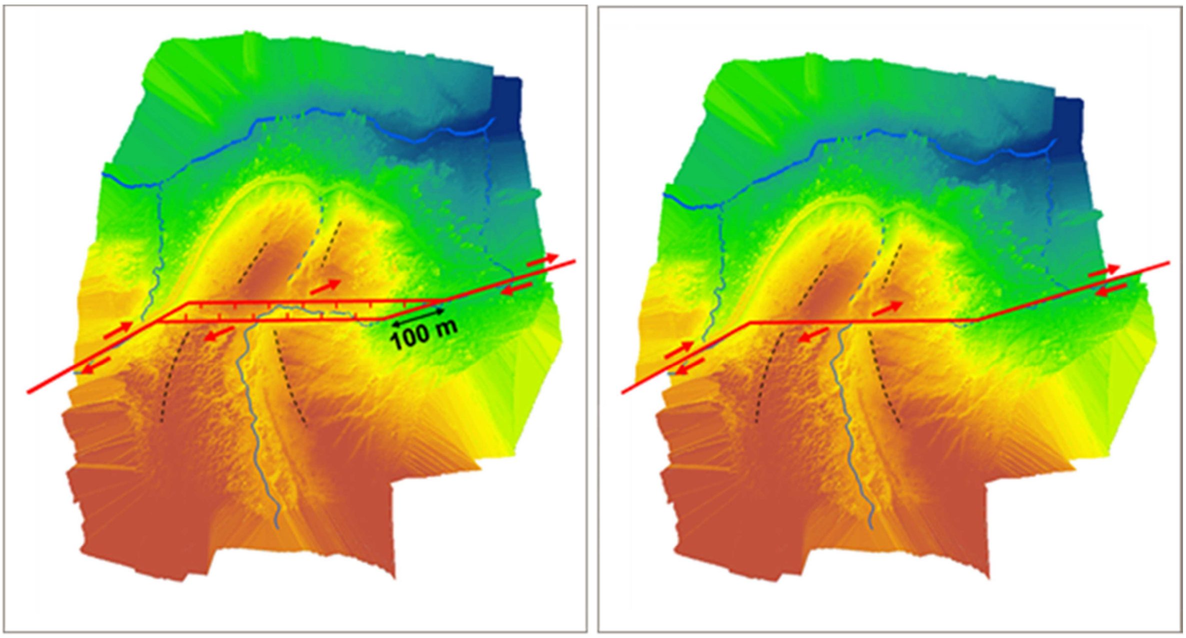


Figure 1: Reconstruction of the fault movement by aligning the topographic elements (moraine crests, abandoned drainage system) on either side of the fault.

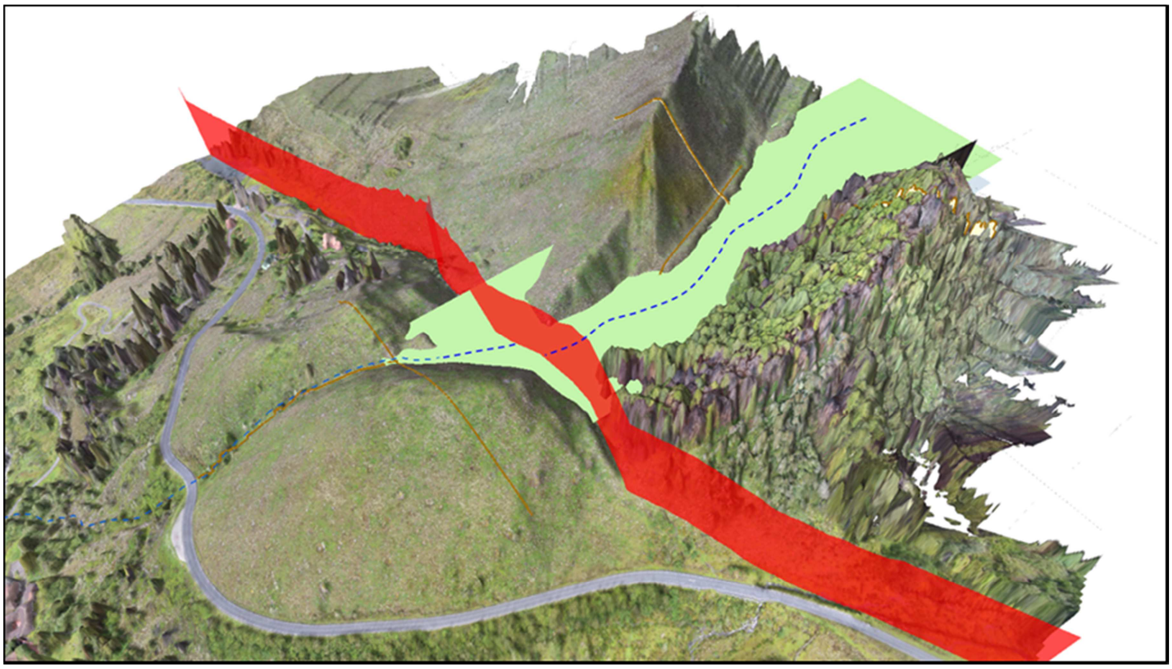


Figure 2: Reconstruction of the original drainage system, before it was disrupted by the fault activity, with the glacial valley filled with sediments and the river flowing out through the frontal moraine.

Integrating geophysical equipment and UAV technology: Considerations and limitations

Maxime Salman

University of Waterloo, 200 University Ave West, Waterloo Ontario N2L3G1, Canada

Key words: *geophysics, advancements, technology, UAV, survey, autonomous, sensor.*

Advancements in geophysical equipment have provided the survey community with lighter and more deployable technologies. Among other advantages, Unmanned Aerial Vehicles (UAVs) benefit from the lack of necessity for an on-board pilot. UAVs can be purchased with optional accessories, such as a global positioning device, and with the advent of automation technology, these aerial devices can fly a survey autonomously based on a programmed flight path.

Prior to combining new lightweight geophysical equipment with autonomous flying devices to undertake surveys, considerations on multiple levels must be made. The cost of UAVs varies by several effective factors; however, payload capacity is possibly the most important one when considering the purchase of a UAV, which can result in thousands of dollars per pound of payload. With an ever increasing focus on field safety, and cost efficiency, alongside the development of smaller and lighter weight geophysical equipment, it is appropriate to use UAVs in airborne surveys.

Airborne geophysical surveys are traditionally designed as orthogonal grids, flown at low altitudes (approx. 80-200 meters above ground), using on-board sensors to measure various physical properties relevant to mining and oil exploration, as well as Governmental research. The sensors vary in size and are being developed to become more lightweight and smaller to account for ease of deployment. This developing ease of deployment is nearly in tandem with easy of flight with ever excelling UAV technology.

Geophysical sensors can be fitted to UAVs to collect data at high rates and stored on board a small memory module on the UAV itself. In addition to sensor fitting, UAV array setups can also be an option, where multiple UAV systems can be flying in formation to collect data, each sensor bearing its own respective combination of geophysical equipment.

Currently, radiometric, mini-gravimetric, and magnetic systems can be carried by higher end fixed-wing and rotor-craft drones, and given the increasing endurance, a moderately sized (50 x 50 km^2) survey block on relatively flat terrain can be conducted within a reasonable timeline.

The elimination of human collateral, and the downsizing of survey aircraft, theoretically allows for more daring investigation at potentially lower altitudes, and with higher vertical tolerances. For example, the current average vertical tolerance for fixed-wing aircraft is 5% gradient, and for rotor-wing is 30%. Modern UAV systems are able to go beyond these tolerances in tougher landscapes, such as the Norwegian fjords, and gather more accurate data.

The future holds much potential for unmanned airborne geophysical surveys, and sensor technology is progressing at an impressive rate. The marriage of UAV technology and sensor technology within the realm of geophysics can be very valuable to service providers and clients, providing those involved with easily obtained, robust data.

Acknowledgements: I would like to sincerely thank the coordinators and those responsible for the VGC 2016 Conference for giving me the opportunity to present my work and to share my experience with others attending.

State of the art 3D visualization of geotopes: A case study of the Cornberg Sandstone

Thomas Schmitz[1], Stefan Rautenberg[1], Heiner Heggemann[2] & Rouwen Lehné[2]

[1] *Technische Universität Darmstadt – Institute of Applied Geosciences, Schnittspahnstraße 9, 64287 Darmstadt, Germany (schmitz@geo.tu-darmstadt.de; rautenberg@geo.tu-darmstadt.de)*
[2] *Hessisches Landesamt für Naturschutz, Umwelt und Geologie (HLNUG), Rheingaustr. 186, 65203 Wiesbaden (heiner.heggeman@hlnug.hessen.de; rouwen.lehne@hlnug.hessen.de)*

Key words: *geotope, photogrammetry, geoscience, sUAS, 3D database.*

The abandoned sandstone-quarry Cornberg is an outstanding geotope in the Federal State of Hessen, Germany, as it is for geoscientific experts as well as for interested laymen of international importance since Permian sandstone deposits host footprints of Permian reptiles and amphibians which worldwide are known from only a few more spots. Furthermore, the local marine sediments of copper shale contain a variety of marine fossils. Due to the great view into the palaeozoic Earth's history, the Hessian Agency for Nature Conservation, Environment and Geology (HLNUG) chose this outcrop as Hessian geotope of the year 2016.

Exposed are sediments of the Permian Rotliegend and Zechstein. The Rotliegend terrestrial sediments are composed of conglomerates at the base and a quarzitic and versatile natural sandstone, the special facies "Cornberg Sandstone Formation", on top. The fossil-bearing Copper shale "Kupferschiefer" marks the beginning of the Zechstein transgression. It is the distinctive marker horizon indicating the marine transgression and the shift between terrestrial Rotliegend deposits towards marine Zechstein deposits, respectively. The marine limestone "Zechsteinkalk" of the Werra Formation is the youngest Permian deposit of the geological sequence in this section.

To adopt new approaches in promoting and preserving such a geotope and to get people interested in geology, the HLNUG decided to start a pilot project in cooperation with the working group Geoinformation of the Technische Universität Darmstadt and the City of Cornberg, which is the owner of the geotope. With the help of a small unmanned aerial system (sUAS) and a DSLR, the area is completely photographed, followed by photogrammetric processing to develop a three-dimensional model. The model consists of three levels of details. One similar to a bird's eye perspective for a general overview of the whole area. Another zooming into the three outcrops of this geotope (Fig. 1) and the third giving impressions of selected sections in high detail. In the next step, the model will be imported into a 3D-database which also supports web-based visualization with nothing but a conventional browser. In addition it is intended to add descriptive annotations in order to explain the main features that can be seen. Due to such a database, geotopes like this will be preserved in its current condition and can still be presented after erosion has taken place or the owner cannot afford the upkeep any longer.

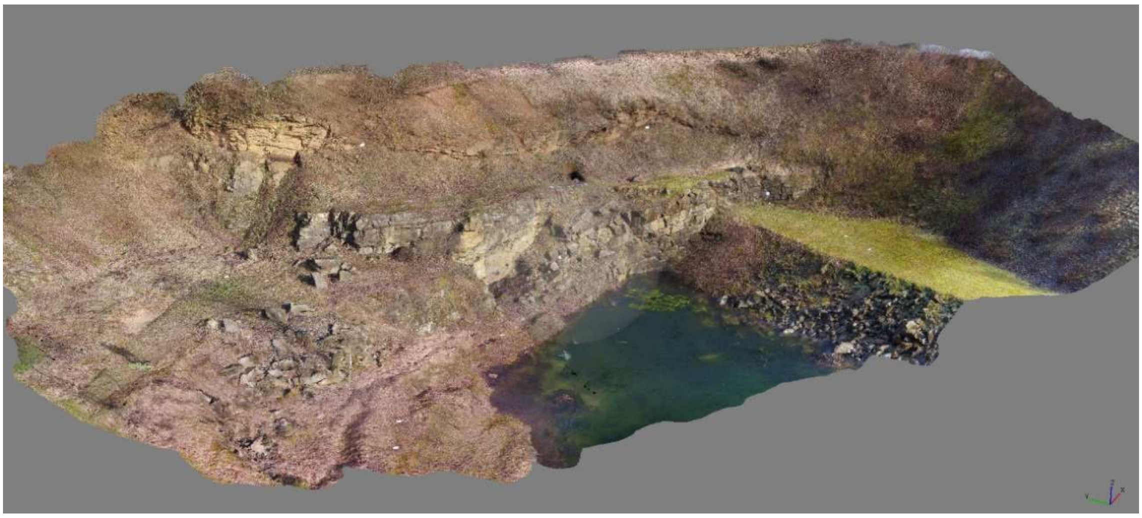


Figure 1: Photorealistic model of one of the three outcrops acquired by aerial imaging using a sUAS and photogrammetric processes.

Making the Arctic accessible: The use of digital outcrops in research and education at 78°N

Kim Senger[1*], Mark Mulrooney[1], Aleksandra Smyrak-Sikora[1], Snorre Olaussen[1], Maria Jensen[1], Alvar Braathen[1,2] & Simon J. Buckley[3,4]

[1] Department of Arctic Geology, University Centre in Svalbard, PO Box 156, 9171 Longyearbyen, Norway; kim.senger@unis.no
[2] Department of Geosciences, University of Oslo, PO Box 1047 Blindern, 0316 Oslo, Norway
[3] Uni Research CIPR, P.O. Box 7810, N-5020 Bergen, Norway
[4] Department of Earth Science, University of Bergen, PO Box 7803, N-5020 Bergen, Norway

Key words: *lidar, photogrammetry, geoscience, UAVs, education, Arctic.*

The University Centre in Svalbard (UNIS) is Norway's "field university", offering BSc, MSc and PhD-level courses to students in natural sciences since being established in 1993. Located at 78°N in Longyearbyen, the administrative centre of the Arctic archipelago of Svalbard, UNIS is strategically placed in a geological paradise comprising exceptional outcrops of the post-Devonian sedimentary succession. Approximately 60% of the archipelago is covered by glaciers, with the remaining land area exposing spectacular outcrops largely devoid of vegetation. The stratigraphic and tectonic history of Svalbard shares many similarities with the Barents shelf, thus outcrops on Svalbard are often studied as analogues to offshore petroleum systems. In addition, the outcrops serve as direct analogues to local subsurface-related activities, including coal exploration and production, hydrocarbon exploration CO_2 storage (e.g., BRAATHEN *et al*., 2012). These outcrops form the backbone of field-based education at UNIS, both in the snow mobile-based spring season and the boat/walking-based summer season. While the high-quality outcrops provide a fantastic link between other subsurface data (e.g., wireline or core data from boreholes, geophysical data sets; Fig. 1), working on Arctic outcrops poses some specific high-latitude challenges, including a 4-month long dark season, extensive snow cover for large parts of the year, steep and often inaccessible cliffs, high logistical and financial cost, and harsh Arctic conditions. To overcome some of these challenges, we have been active users of modern virtual geology techniques since 2008 and use this opportunity to share some of our experiences in both education and research.

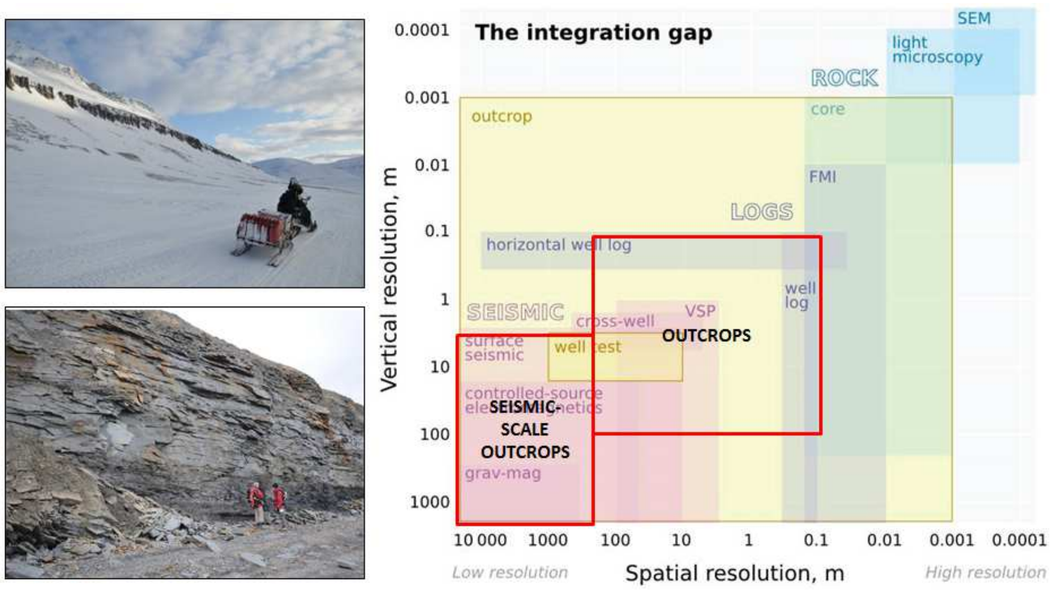


Figure 1: Outcrops at different scales. Left: Typical Svalbard outcrops during spring (above) and summer (below). The upper image illustrates good exposure of a dolerite sill exposed for ca 10 km at Wallenbergfjellet. The lower image is of the Longyearbyen CO2 lab target reservoir near Deltaneset, where outcrop studies complement borehole data. Right: Summary of data sets typically used in subsurface characterization, as a function of the vertical and lateral resolution. Outcrop studies on Svalbard are designed to complement existing subsurface data within the indicated spatial ranges. Figure modified from Matt Hill (Agile Geoscience).

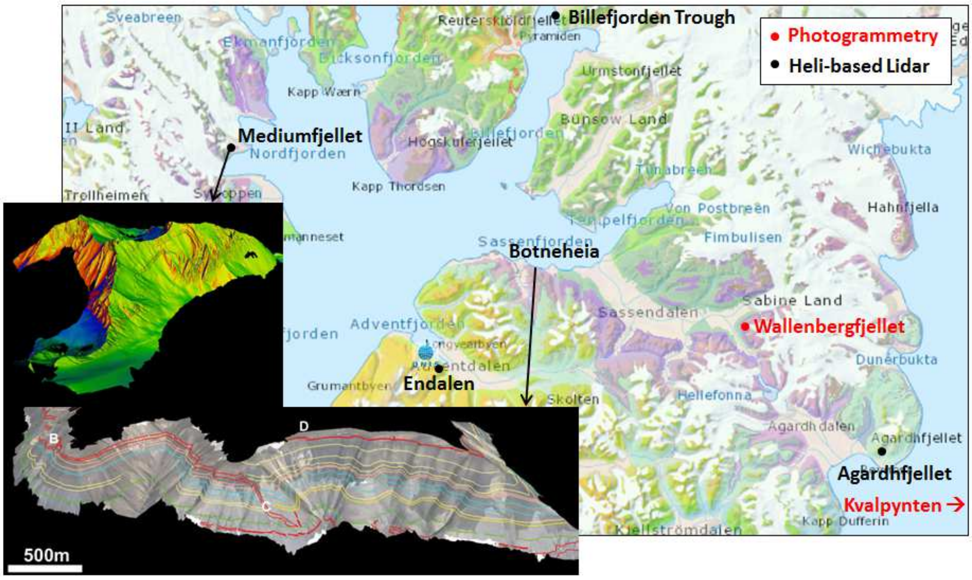


Figure 2: Overview of the digitized outcrops acquired by UNIS and partners in Spitsbergen since 2008. The outcrops cover a range of geological units, tectonic settings and outcrop scales. Base geological map provided by the Norwegian Polar Institute.

Initial applications of virtual outcrop methods at UNIS involved the acquisition of costly helicopter-borne lidar scans which were used as a basis for studying the geometries of sedimentary and structural features in a variety of geological settings (Fig. 2; BUCKLEY *et al*., 2008). The Botneheia 3D model (Fig. 2), for instance, was used to map and quantify the nature of the igneous intrusions within the Longyearbyen CO_2 lab reservoir (SENGER *et al*., 2013). The same data set was also used to quantify the sedimentary heterogeneity of the target aquifer and tie sedimentary logs together. In addition, the dataset became an integral part of numerous UNIS BSc term projects as well as MSc theses. An additional lidar-based 3D outcrop model of Mediumfjellet (Fig. 2) was used primarily to visualize and quantify the structural features evident in the West Spitsbergen fold-and-thrust belt. More recently, 3D outcrop models have been constructed using photogrammetry, acquired both onshore (handheld or using drones) and offshore in Svalbard's fjords (from small boats). Typically these models are used for quantifying the large-scale geometry (i.e. "seismic-scale outcrops"), to plan the field activity and subsequently to tie detailed field observations (e.g., sedimentary logs, structural measurements, photographs, sample locations etc.) directly to the outcrop. Such outcrops are also of key importance for onshore-offshore correlations through, for instance, forward modelling of seismic data (e.g., LECOMTE *et al*., 2015). In addition, detailed high-resolution and georeferenced photogrammetric models of smaller outcrops are used for both automatic and manual natural fracture mapping, such as at intrusion-host rock interfaces. Current work at UNIS is focussing on optimizing the integration of the virtual outcrops with other surface (e.g., geological and topographical maps, satellite images, sedimentological) and subsurface (e.g., seismic, boreholes) data sets. To conclude, we have a broad experience of using modern virtual geology tools at numerous spatial scales to make full use of the opportunities offered by Svalbard's unique geological exposures.

References

BUCKLEY, S.J., VALLET, J., BRAATHEN, A. & WHEELER, W., 2008. Oblique helicopter-based laser scanning for digital terrain modelling and visualisation of geological outcrops. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37(B4): 493-498.

BRAATHEN, A., BÆLUM, K., CHRISTIANSEN, H.H., DAHL, T., EIKEN, O., ELVEBAKK, H., HANSEN, F., HANSSEN, T.H., JOCHMANN, M., JOHANSEN, T.A., JOHNSEN, H., LARSEN, L., LIE, T., MERTES, J., MØRK, A., MØRK, M.B., NEMEC, W.J., OLAUSSEN, S., OYE, V., RØD, K., TITLESTAD, G.O., TVERANGER, J. & VAGLE, K., 2012. Longyearbyen CO2 Lab of Svalbard, Norway – First Assessment of the sedimentary succession for CO2 storage. *Norwegian Journal of Geology*, 92: 353–376.

LECOMTE, I., LAVADERA, P.L., ANELL, I., BUCKLEY, S.J., SCHMID, D.W. & HEEREMANS, M., 2015. Ray-based seismic modelling of geologic models: Understanding and Analyzing Seismic Images Efficiently. *Interpretation*, 3(4): SAC71-SAC89.

SENGER, K., ROY, S., BRAATHEN, A., BUCKLEY, S.J., BÆLUM, K., GERNIGON, L., MJELDE, R., NOORMETS, R., OGATA, K., OLAUSSEN, S., PLANKE, S., RUUD, B.O. & TVERANGER, J., 2013. Geometries of doleritic intrusions in Central Spitsbergen, Svalbard: An integrated study of an onshore-offshore magmatic province with implications on CO2 sequestration. *Norwegian Journal of Geology*, 93: 143-166.

Change detection using baselines extracted from single scans demonstrated on a masonry wall subject to seismic testing

Yueqian Shena[1,2,*], Roderik Lindenbergh[1] & Jinhu Wanga[3]

[1] *Dept. of Geoscience and Remote Sensing, Delft University of Technology, Building 23, Stevinweg 1, Post Box 5048, 2628CN Delft, The Netherlands; (y.shen-2, r.c.lindenbergh, jinhu.wang)@tudelft.nl*

[2] *School of Earth Science and Engineering, Hohai University, No. 1 Xikang Rd., 210098 Nanjing, China**

[3] *Key Laboratory of quantitative Remote Sensing Information Technology, Academy of Opto-Electronics, Chinese Academy of Science*

Key words: *terrestrial laser scanning, baselines, masonry wall, seismic testing, change detection.*

Terrestrial laser scanning (TLS) technology has developed significantly in recent years and is increasingly used in fields such as geomorphology, city management and structural monitoring. For many applications, changes are detected between, say, two scans obtained from the same scene at two different times. Traditionally, these two scans are aligned into a common coordinate system using a so-called registration method. A disadvantage of such an approach is that this registration step introduces additional errors in the processing flow. Another problem is that any registration method requires some stable targets or features, while in practice it is unfortunately often not guaranteed that even targets placed by surveyors remain untouched between two different scans.

To overcome these issues we propose instead to compare corresponding baselines extracted independently in each of the two scans. Here a baseline is defined as a 3D line segment connecting two points in one scan. Two baselines from different scans are corresponding if they connect the same features. As features we propose to use two type of points. First, target points identified by spherical or planar targets as placed by the surveyor in the scene and, second, so-called virtual points, which give the 3D location of a feature that is well-recognisable from the 3D scan data. What virtual points are suitable depends on the particular scene that is considered.

This proposed methodology is illustrated to detect changes on a masonry building during seismic testing, mainly for monitoring purposes but also to be able to provide change information for further structural analysis. In this case, as in most cases, target points are easily identified in the scan data. The extraction of virtual points requires more work. In this case we choose as virtual points the centres of bricks. In the building scan, one wall is available that is expected to be stable, while another wall is actually cracked during the seismic testing.

The extraction of virtual points starts with separation of mortar and bricks in the scan data using k-means clustering of the TLS intensity attribute. Next, point clouds are segmented and 3D virtual point locations are estimated at the brick centres. Given both the resulting target points and virtual points, baselines are constructed as indicated in Fig. 1. Finally, by comparing corresponding baselines from the two epochs, changes in X, Y and Z direction of a suitable structural coordinate system are extracted.

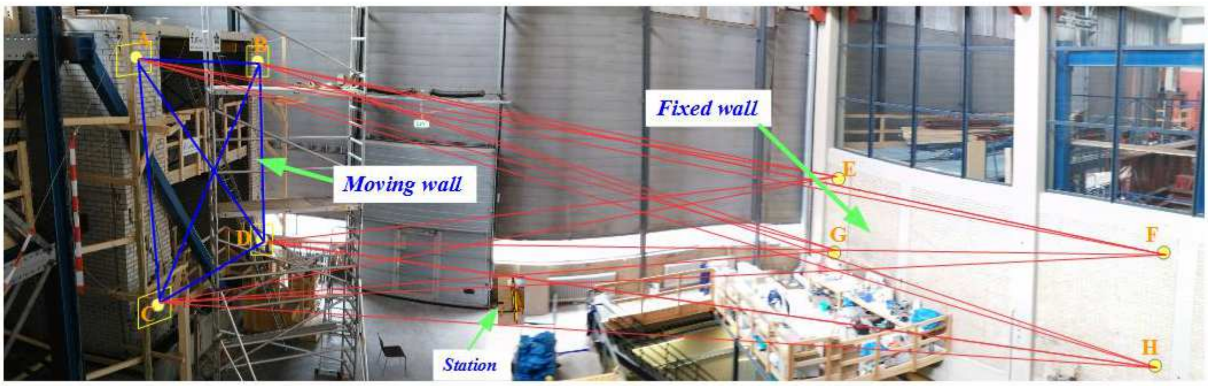


Figure 1: baselines between feature points in a single scan, here illustrated by a photo of the scanned scene. On the left a brick wall that gets damaged by seismic testing, on the right a brick wall that is assumed to be stable. Baselines are constructed in a single scan and do not require registration.

As a validation, results are compared to results from traditional methods. That is, for a traditional approach, scan data is first registered in a common coordinate system. Next, cloud-to-cloud distances and cloud-to-mesh distances between the aligned points clouds are extracted. As a mix between traditional and proposed method, also baselines connecting feature points from different epochs after registration are added to the comparison. As a first benefit of the proposed method we were able to identify a target that was apparently moved by an external agent early in the processing workflow. A detailed analysis of the change results will be presented in the final presentation. To summarize, the proposed method is a new, alternative approach for change detection that eliminates an often unnecessary registration step and its associated errors.

Acknowledgements: We would like to thank the China Scholarship Council (CSC) for enabling Yueqian Shen to study for one-year at the Department of Geoscience and Remote Sensing, TU Delft.

Detailed structural mapping of syn-rift deposits by incorporating lidar data in reservoir modelling software

Espen Sigmundstad*, Chris Townsend & Alejandro Escalona

The University of Stavanger, P.O. Box 8600, Forus N-4036 Stavanger, Norway; espen_sigmundstad@msn.com

Key words: *geology, lidar, 3D modelling, Petrel E&P.*

This study is located in a half-graben on the southern margin of the active Corinth rift in Greece where a thick unit of alluvial/fluvial sedimentary rocks outcrop. Previous studies suggest that this thick sedimentary unit is related to syn-rift deposition during the early stages of rifting (FORD *et al.*, 2013). However, outcrop characteristics such as growth strata and syn-depositional unconformities that would support this interpretation are not clearly visible. Therefore, the main objective for this project was to utilize light detection and ranging (lidar) data combined with field data to build a consistent 3D model that allows better understanding of the thick unit of alluvial/fluvial sediments filling the half-graben.

The lidar data utilized in this project (Fig. 1) covers an area of approximately 11 km² and provides full 360° coverage of the alluvial/fluvial sediment outcrop. Petrel E&P was used as a platform to trace individual layers, interpret faults, measure thickness variations along individual layers, estimate dip and dip direction of individual layers, determine angular relationships between different parts of the outcrop and to correlate layers across the mountain. Fault interpretations, unconformities and other observations derived from field mapping was also integrated as a part of the Petrel E&P dataset.

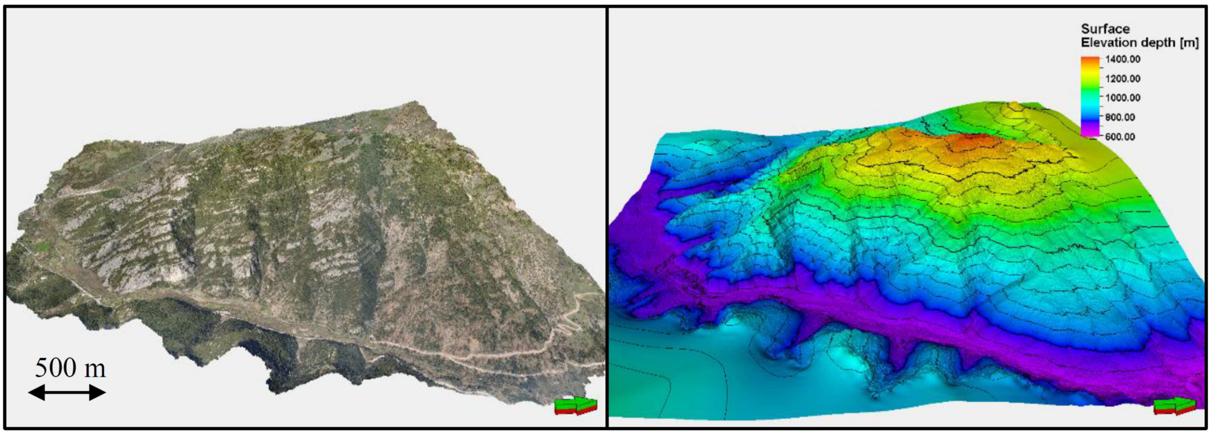


Figure 1: Left image overview of coloured LiDAR point cloud, right image represents DEM surface of lidar point cloud with elevation contours. Green and red arrow points towards the north.

Interpretation and analysis of the dataset indicate that both faulting and complex internal layering of the alluvial/fluvial sediments dominate the outcrop. Lateral thickness variations occur both in the north-south and east-west directions, this further complicates correlation over any significant distance. 3D structural models were created to analyse different interpretations and compare with the actual outcrop; Fig. 2 is an example of one of the models created. The level of detail captured in the 3D model because of the lidar dataset made it possible to group different layers in the outcrop and relate them to distinct phases. As a final result, geological constraints are established for better understanding the half-graben infill and structural evolution of the infill.

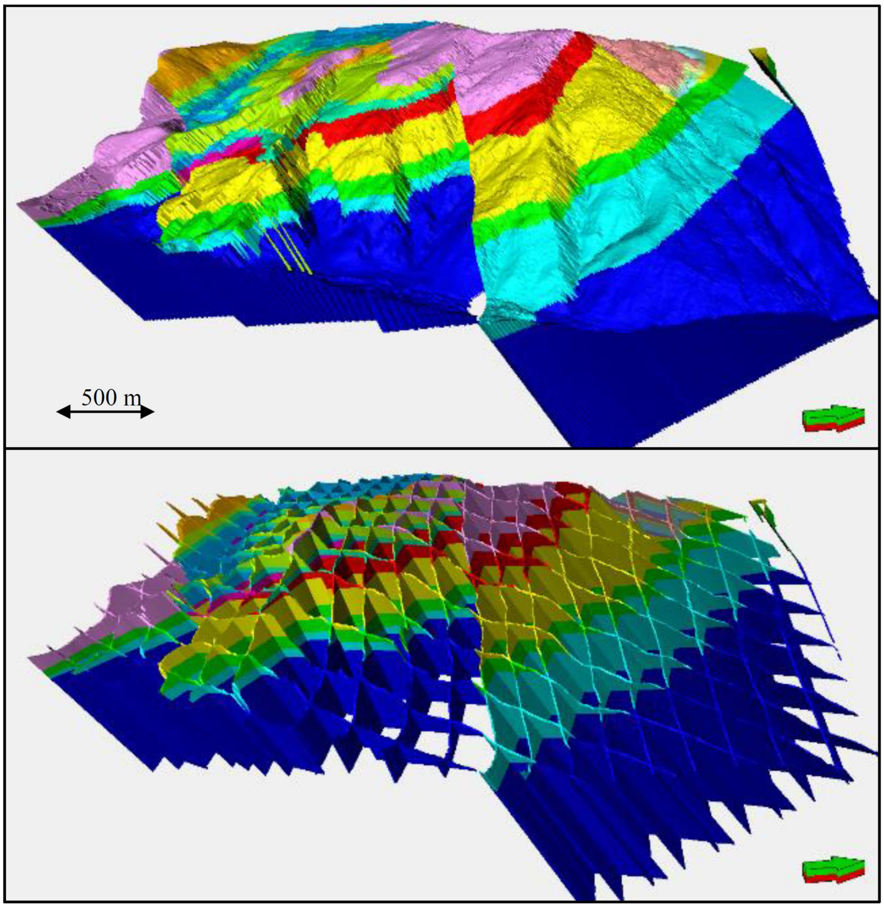


Figure 2: Top image displays structural model result, bottom picture with index filter to display internal skeleton of model.

Acknowledgements: Utmost gratitude to the University of Stavanger in funding this project through the "Petroleum Student Fund". In addition, a huge thanks to Heidelberg University in Germany for the lidar data supplied for this project and for helpful advice throughout processing of the lidar data.

Reference

FORD, M., ROHAIS, S., WILLIAMS, E. A., BOURLANGE, S., JOUSSELIN, D., BACKERT, N., & MALARTRE, F., 2013. Tectono-sedimentary evolution of the western Corinth rift (Central Greece). *Basin Research*, 25(1): 3-25.

Three-dimensional model of facies distribution within a Triassic half-graben, SW Edgeøya, Svalbard.

Aleksandra Smyrak-Sikora[1,3*], Per Terje Osmundsen[1,2], Alvar Braathen[1,4], Mark Mulrooney[1,4] & Snorre Olaussen[1]

*[1] University Centre in Svalbard, P.O. Box 156, 9171, Longyearbyen, Norway, *aleksandras@unis.no*
[2] Geological Survey of Norway, 7491 Trondheim, Norway
[3] Department of Earth Science, University of Bergen, P.O. Box 7800 N-5020 Bergen, Norway
[4] Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, 0316 Oslo, Norway

***Key words:** three-dimensional model, photogrammetry, facies analysis, Triassic, Svalbard.*

An array of ten sedimentary basins of Upper Triassic age outcrop along the steep cliff section of the Kvalpynten peninsula (Edgeøya, Svalbard, Fig. 1A), forming a world-class locality for studying the sedimentary fill of half-graben and graben basins (OSMUNDSEN *et al.*, 2014). A series of 5000 geo-tagged photographs of the 9 km long cliff section were taken and used to create a 3-dimensional photogrammetric model (Fig. 1C). The primary aim of the study is to investigate the gross geometry of the syn-kinematic packages with emphasis on the nature and style of the sedimentary fill and growth faults.

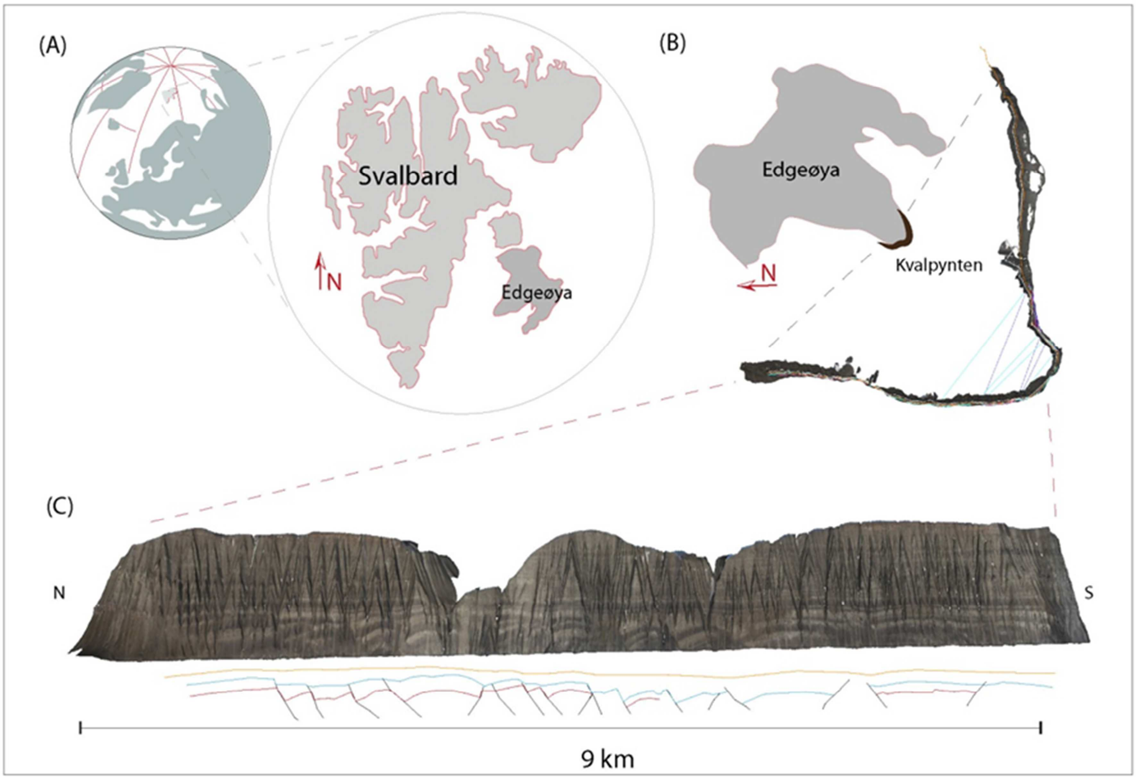


Figure 1: (A, B) Location of the study area on Edgeøya, Svalbard. (C) Kvalpynten photogrammetric model (upper, vertical exaggeration 1,7x) and interpretation (lower) produced in the LIME software, showing ten sedimentary basins exposed in the lower part of the cliff. Two potential basin correlations across the peninsula are marked with blue and purple in (B).

Integrated field studies (sedimentary logging and structural measurements) along with remote measurements from the photogrammetric model allowed the creation of a three-dimensional model of sedimentary facies distribution. Based on photogrammetric model interpretation, two potential correlations of a single basin (Fig. 1B) across two orthogonal cliff sections were investigated. Field-based sedimentological and structural data analysis helped to establish a unique interpretation where the individual basin is identified in both outcrops based on similarities in faults activity with respect to interpreted flooding surfaces (blue, orange and red lines (Fig. 1C). The three-dimensional model of facies association distribution illustrates variation along the fault strike formed in response to the differential displacement along the basin-bounding faults.

Analysis of the large-scale geometry provided by the photogrammetric model in combination with field-based observations results in better understanding of the three-dimensional syntectonic sedimentary architecture within an extensional basin. The position of Kvalpynten basins at the edge of the Svalbard archipelago makes it a perfect location for offshore correlations with Barents Shelf Triassic deposits.

Acknowledgements: I would like to acknowledge all participants of the Edgeøya 2012 and 2014 field parties, and to thank Simon Buckley for providing the Kvalpynten photogrammetric model. This study is part of the Trias North Project hosted by University of Oslo and funded by the Research Council of Norway, Tullow Oil, Statoil, Lundin Norway, Edison Oil and RWE Dea.

Reference

OSMUNDSEN, P. T., BRAATHEN, A., RØD, R. S., & HYNNE I. B. 2014. Styles of normal faulting and fault-controlled sedimentation in the Triassic deposits of Eastern Svalbard. *Norwegian Petroleum Directorate Bulletin*, 11: 61-79.

Mapping Paleoproterozoic meta-volcanic rocks using photogrammetry

Erik Vest Sørensen[1*]

[1] *Geological Survey of Denmark;evs@geus.dk*

Key words: *photogrammetry, geoscience, 3D mapping, meta-volcanics.*

A newly discovered succession of Paleoproterozoic meta-volcanic rocks from a remotely located part of West Greenland (71°-72°20´N) was investigated using photogrammetry. Stereo-images were collected during fieldwork using hand-held cameras deployed from a boat, helicopter and on foot walking along outcrops. The presented data is part of a larger dataset (approximately 25,000 oblique stereo-images) collected during a regional assessment of the zinc mineral potential of the Karrat region. We used a structure from motion (SfM) approach for tie point generation using the commercial version of Agisoft PhotoScan. The raw image matches were imported into the 3D StereoBlend photogrammetric software for triangulation and subsequent stereoscopic feature extraction and geological interpretation. GPS data collected together with the images during fieldwork were used as a first approximation to the absolute positioning while subsequent refinement of the absolute positioning during the bundle adjustment were obtained by pass points collection in monochrome aerial photographs. The meta-volcanic succession is exposed in a steep cliff side of the Kangilleq Fjord and is partly inaccessible (Fig. 1).

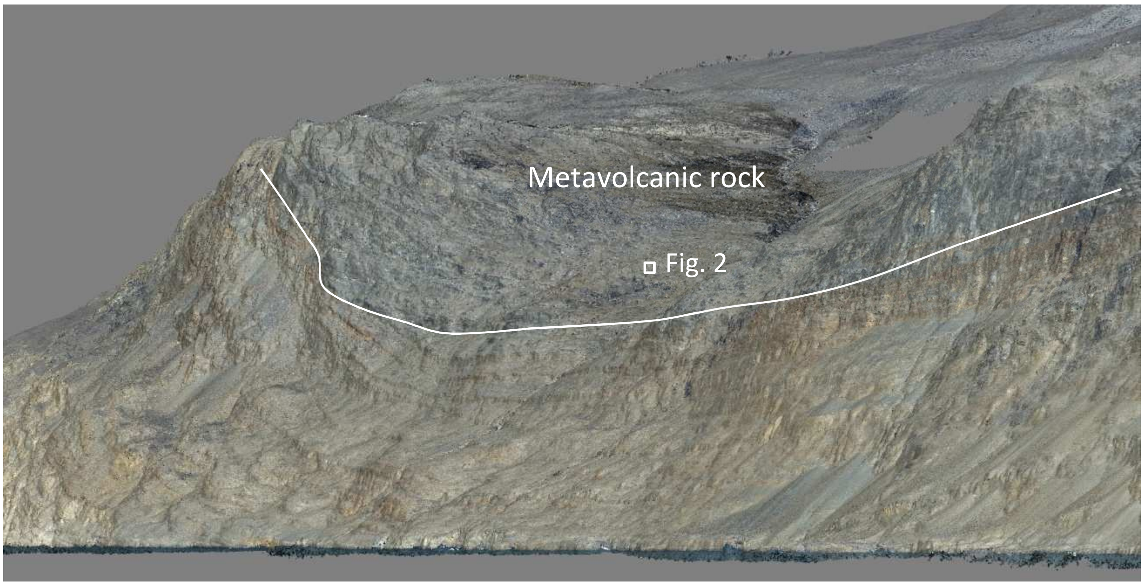


Figure 1: Image (point cloud) showing the Kangigdleq Formation meta-volcanic rocks at Qangátarssuaq, West Greenland. The meta-volcanic rocks are found in a small synformal structure as highlighted by the white line. Inset box indicates the approximately position of Fig. 2. Field of view is approximately 3000 m and the cliff rises from sea-level to approximately 1100 m above sea level.

Images collected from helicopter and boat were used to map the overall structure of the area while a combination of images taken with a small low-cost digital camera and a tablet camera was used to document close-up details of selected outcrops in the more accessible part of the area. This is illustrated in Fig. 2, which shows a reconstruction of some of the primary pillow structures that are found preserved in the area. The presented data illustrate how digital imagery can be utilized to efficiently map an area that would have been otherwise difficult to investigate. It also illustrates how the digital data can be used in efficient planning of subsequent fieldwork to be conducted during 2016.

Figure 2: Image (point cloud) showing a close-up representation of a succession of relatively well-preserved pillow-lava found in the steep cliffs of Kanigilleq Fjord.

Regional geological 3D-mapping in Alpine terrain: An example of a large oblique image-block from West Greenland

Erik Vest Sørensen[1*], Pierpaolo Guarnieri[1] & Diogo Rosa[1]

[1] *Geological Survey of Denmark; evs@geus.dk*

Key words: *photogrammetry, geoscience, 3D mapping, remote, Arctic.*

The geology of the Karrat region (71°-72°20´N) West Greenland was investigated in terms of its zinc mineral potential. The studied area is remotely-located and is characterized by steep alpine terrain with up to 2000 m of relief that in many places is completely inaccessible. This makes fieldwork an extremely difficult task where a successful outcome is highly dependent on remotely-sensed observations in combination with reconnaissance observations.

The logistical platform during fieldwork consisted of a boat, which served as a base camp, and helicopter support for day excursion and putting out field camps. It was decided, in an early stage of the planning phase, to collect stereo-images whenever possible and with the main purpose of geological interpretation. This resulted in the collection of a unique dataset with around 25,000 oblique stereo-images (Fig. 1) acquired during the field campaign that lasted one month.

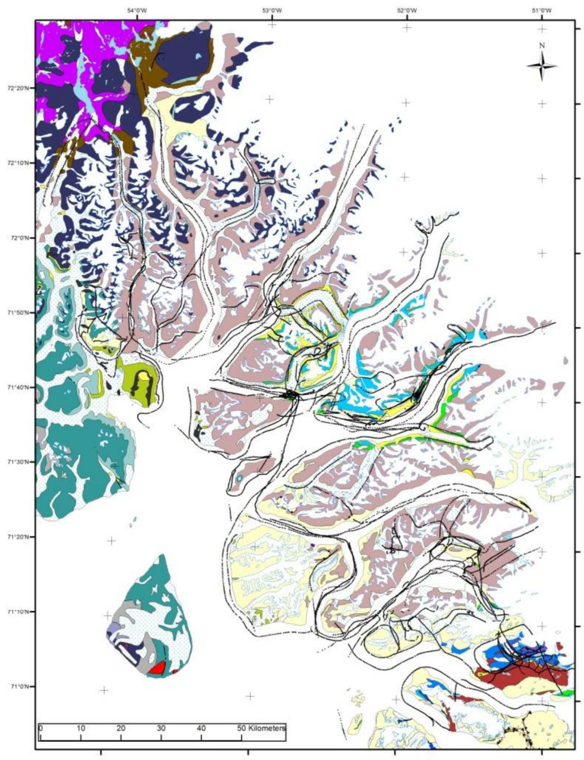


Figure 1: Image showing the image stations (black dots) of the large regional oblique image-block.

The images were collected from helicopter and boat using a handheld calibrated Nikon D800E (36 megapixel) digital SLR camera equipped with a fixed Carl Zeiss Distagon 35 mm lens. The images were typically collected in a linear fashion parallel to the cliffs at varying distance when travelling between locations. The relative connectivity between the images was established using a structure from motion (SfM) approach using Agisoft PhotoScan. Although not originally planned for, there is sufficient connectivity between individual stereo-lines to combine individual lines (up to around 100 km in length) into an interconnected framework of stereo-lines. GPS data collected with the images were used to place the models in absolute space and the large oblique image-block covers around 13,000 km^2. The images were subsequently imported into 3D StereoBlend from Anchor Lab for refinements of the bundle adjustment and subsequent stereoscopic feature extraction of key horizons and correlation between fiords. The area is structurally complex and deformed. An example of this is given in Fig. 2. Once key horizons have been mapped, the area would ultimately have to be structurally-restored using 3D modelling software.

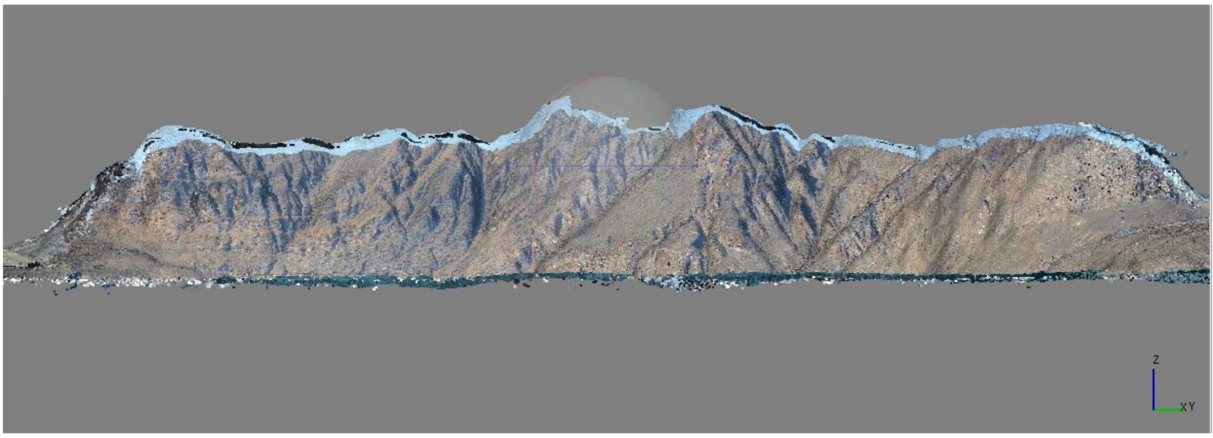


Figure 2: Photorealistic representation of the Karrat Island, West Greenland. Field of view is approximately 10 km and the peaks in the central part have an elevation of 1100 m above sea level.

Mapping mountain-scale thrust zones using photogrammetry: Examples from the French Alps

Yukitsugu Totake[1,2*], Robert Butler[1] & Clare Bond[1]

[1] *Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, UK; yukitsugu.totake@abdn.ac.uk*

[2] *Technical Resources Unit, INPEX CORPORATION, Tokyo, Japan*

Key words: *photogrammetry, structural geology, field mapping*

Recent advances in photogrammetric technology have dramatically facilitated acquisitions of high resolution 3D geospatial data for geoscience and geoengineering studies at multiple scales, from rock specimen to landscape. Modern photogrammetry techniques only require limited infrastructure, while offering high portability and acquisition of high quantity data in a short time. Geological field surveys are one area expected to benefit from the technique. High-resolution 3D scenes reconstructed by photogrammetry techniques can provide visualisations for better understanding of the 3D nature of targets of interest, whilst also providing densely distributed data that, together with directly observed additional field data, can be used for building geological interpretations and models. Incorporation of modern photogrammetry techniques with field surveys is quite easy and has great potential to enhance performance of the surveys particularly in inaccessible terrains.

Here we report a case study of mountain-scale field mapping executed in the Western Champsaur basin, SE France, using ground-based photogrammetry. The basin, developed as an early Alpine fore-deep basin, is located c. 20 km northeast of Gap, and extends approximately 10 km from east to west and 6 km from north to south. The basin is filled by Eocene-Oligocene turbidite successions, the Champsaur Sandstone that overlies transgressive Nummulitic limestones and hemipelagic marls. The Champsaur Sandstone displays complex structural styles of faulting and folding through well-layered sandstone-shale sequences that are challenging to map by conventional field survey. During two weeks of fieldwork across the basin, over 9,400 photographs were taken by a handheld digital camera from 133 ground location points, georeferenced with a handheld GPS. The photographic images were processed within the software PhotoScan Pro to build 3D landscape scenes. The constructed photogrammetric models were then imported into Move software to map faults and sedimentary layers. Georeferenced field data was integrated into the model (Fig. 1), so that geological cross sections and 3D geological surfaces could be produced.

The photogrammetric models built provided morphology and texture of the landscape at metre resolution, which is sufficiently higher than free digital elevation model data and detailed enough for understanding the structural style of the thrust zone at a scale of over 100 m. Polylines of sediment beds and faults traced on the photogrammetry models allowed interpretation of a pseudo-3D geometry of the deformation structures, and enabled prediction of dips and strikes from inaccessible field areas, to map the complex geometries of the thrust faults and deformed strata in detail. Although, deliberate planning for data acquisition is mandatory in order to achieve a good coverage and resolution of photographs to create a complete model, the use of photogrammetry techniques can add great value to geological field surveys.

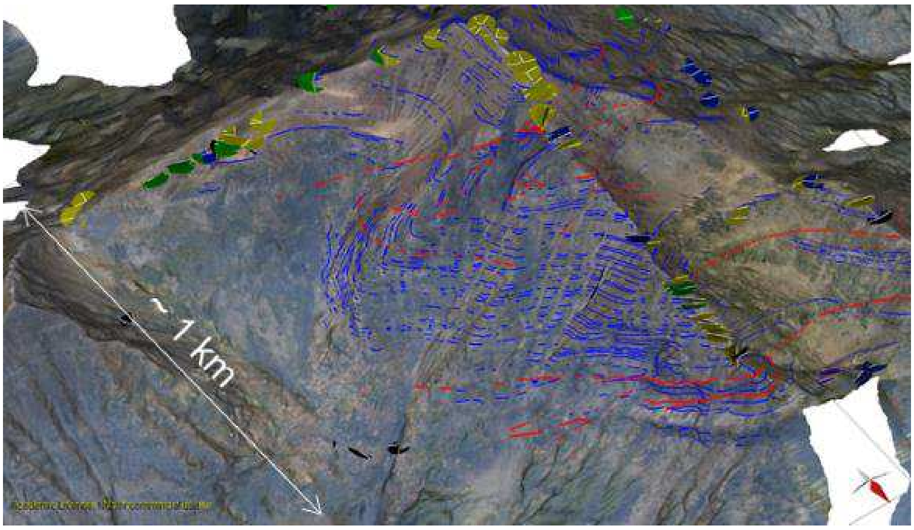


Figure 1: Structural mapping of landscape model reconstructed using ground-based photogrammetry techniques. Disc symbols (green and yellow) show structural data collected during the field survey, blue lines are the traces of sedimentary layers and red lines represent fault traces.

Acknowledgements: This study is based on PhD research project funded by INPEX CORPORATION at University of Aberdeen.

Across spatial scales: Snow depth from combined satellite and airborne lidar

Désirée Treichler[1*], Andreas Kääb[1] & Kjetil Melvold[2]

[1] *Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, 0316 Oslo, Norway; desiree.treichler@geo.uio.no*

[2] *Norwegian Water Resources and Energy Directorate (NVE), P.O. Box 5091 Majorstua, N-0301 Oslo, Norway*

Key words: *satellite altimetry, lidar, snow depth, cross-scale.*

Direct snow depth measurements are sparse, especially in remote areas. We present a method to retrospectively derive snow depths from ICESat satellite laser altimetry for its operational period (2003-2009) by comparing the data with high-resolution digital elevation models (DEMs). The study site is the Hardangervidda plateau in southern Norway. Hardangervidda is the largest mountain plateau in northern Europe. Globally consistent ICESat surface elevation measurements with circular footprints of 70 m in diameter are compared to reference elevations from DEMs with different cell sizes to receive elevation differences (dh). Three DEMs are used: The SRTM DEM (90 m spatial resolution), the Norwegian national DEM (10 m), and a high-resolution lidar DEM (2 m). dh are expected to be zero for ICESat's snow-free campaigns. Snow cover during ICESat's winter campaigns typically results in positive dh which correspond to snow depth.

We find that snow-free dh are distinctly smaller if a high resolution lidar DEM is used than in case of the Norwegian National DEM or the SRTM DEM. High resolution DEMs for small areas do not have the spatial inconsistencies of lower resolution reference DEMs – a result of the typical spatio-temporal merging of different datasets to cover larger areas. The DEM biases of the national and global DEMs exceed ICESat elevation uncertainty by an order of magnitude, and are thus limiting the accuracy of the method, rather than ICESat uncertainty.

ICESat-derived snow depths from winter dh agree very well with measured and modelled snow depths in the Hardangervidda area, but only if samples are grouped spatially and into elevation bands. Using the high-resolution lidar DEM, even single footprints show very good agreement with measured snow depths from the same year. The lower uncertainty allows for finer spatial resolution of ICESat-derived snow depths. By combining elevation data across spatial scales, uncertainties in snow depth estimates or other ICESat-derived parameters can thus be greatly reduced. Good quality reference DEMs may still be acquired in future even in areas where no such data exists today.

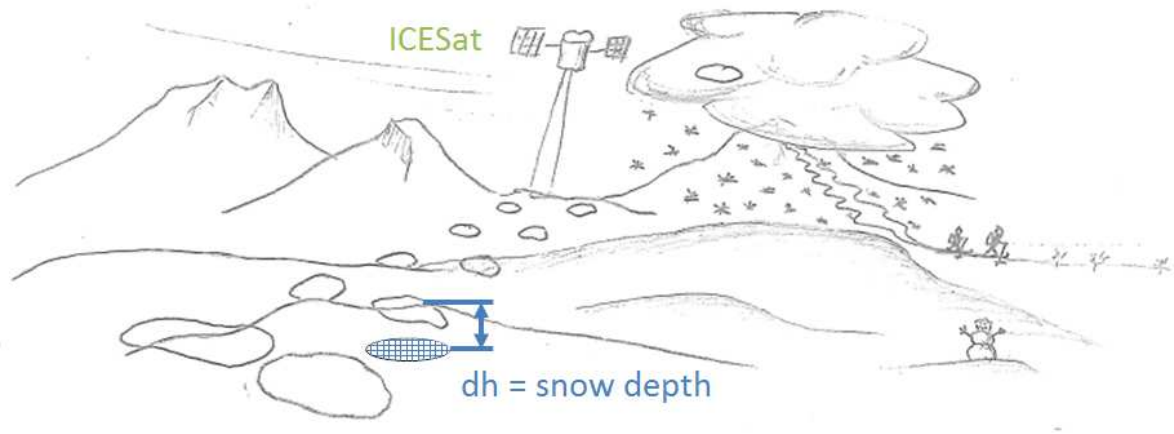


Figure 1: Snow depth from ICESat laser satellite winter surface elevations compared to reference elevations from high-resolution airborne lidar.

Mapping geological structure on mountain-scale photogrammetric models generated from national survey vertical aerial photos (Kamnik Alps, Slovenia)

Marko Vrabec[1*] & Erazem Dolžan[1]

[1] *University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geology, Aškerčeva 12, Ljubljana, Slovenia; marko.vrabec@geo.ntf.uni-lj.si*

Key words: *photogrammetry, structural geology, geological mapping.*

Mountainous regions such as the Alps offer excellent insight into 3D geological structure due to their extreme topographic relief and good bedrock exposure. Since the steep and rugged mountain landscape is often inaccessible to fieldwork, structural interpretation of detailed photogrammetric 3D terrain models can provide a good alternative to conventional mapping methods. Obtaining imagery for photogrammetric reconstruction is not easy, however. Complex flight paths and large vertical and horizontal distances involved in covering the mountainous terrain, in addition to strong winds and unstable weather greatly complicate image acquisition by UAVs, whereas renting commercial aircraft is often too costly for academic research projects.

For our structural analysis of the central Kamnik Alps of northern Slovenia we used vertical aerial photographs originally acquired by the Surveying and Mapping Authority of the Republic of Slovenia for surveying purposes. Image resolution is 17310 x 11310 pixels and corresponding ground coverage is approx. 3.7 x 2.5 km with ~25 cm ground resolution. Our 7.5 km x 4.3 km study area is covered by 27 images acquired in 2 flight strips, ensuring a high degree of overlap between the images. We processed the images with Agisoft PhotoScan structure from motion photogrammetric software to generate textured surface models of the terrain. Due to predominance of steep cliffs reaching 300-400 m in height and high terrain ruggedness we generated the terrain model in arbitrary 3D surface mode rather than in DEM mode. The resulting model was generally very good. Gaps in the surface mesh occur only at isolated cliff sections which are near-vertical to vertical, whereas for the rest of the steep cliffs both the 3D mesh and the texture are completely satisfactory.

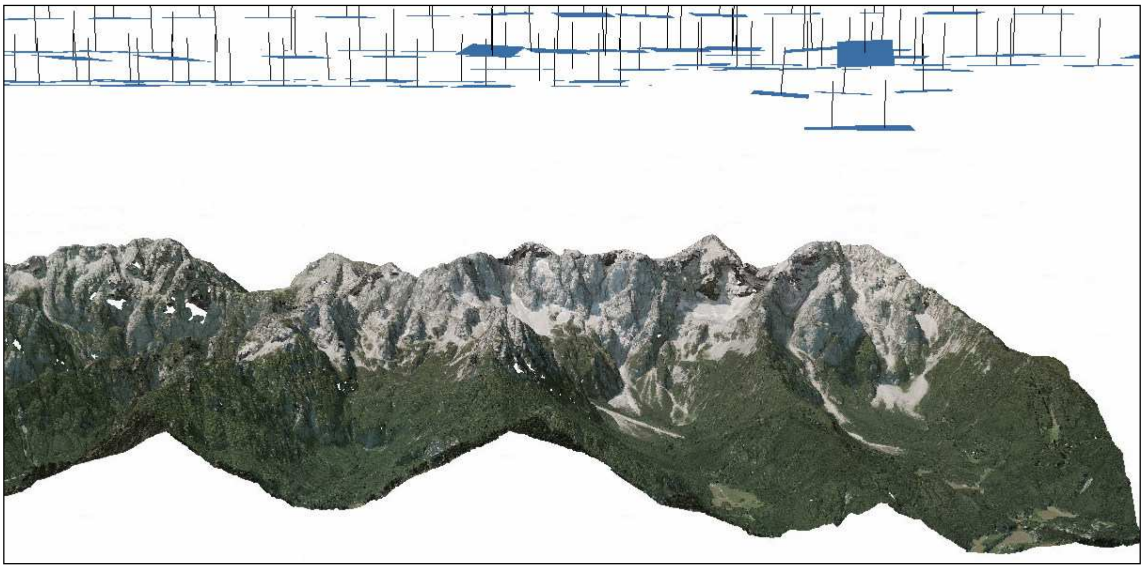


Figure 1: Photogrammetric model of the central Kamnik Alps with aerial photo positions (view from the North).

We exported the textured 3D surface to MVE Move structural interpretation software, which in version 2016 added support of arbitrarily shaped textured models, a great improvement over previous versions for working with photogrammetric models. Move software offers a range of digital mapping and interpretation tools for mapping of traces and surfaces of faults and stratigraphic boundaries and determining dips of structural planes.

Photogrammetric model analysis was complemented by georeferenced geological field data acquired along mountain trail transects, mainly using the MVE FieldMove software application.

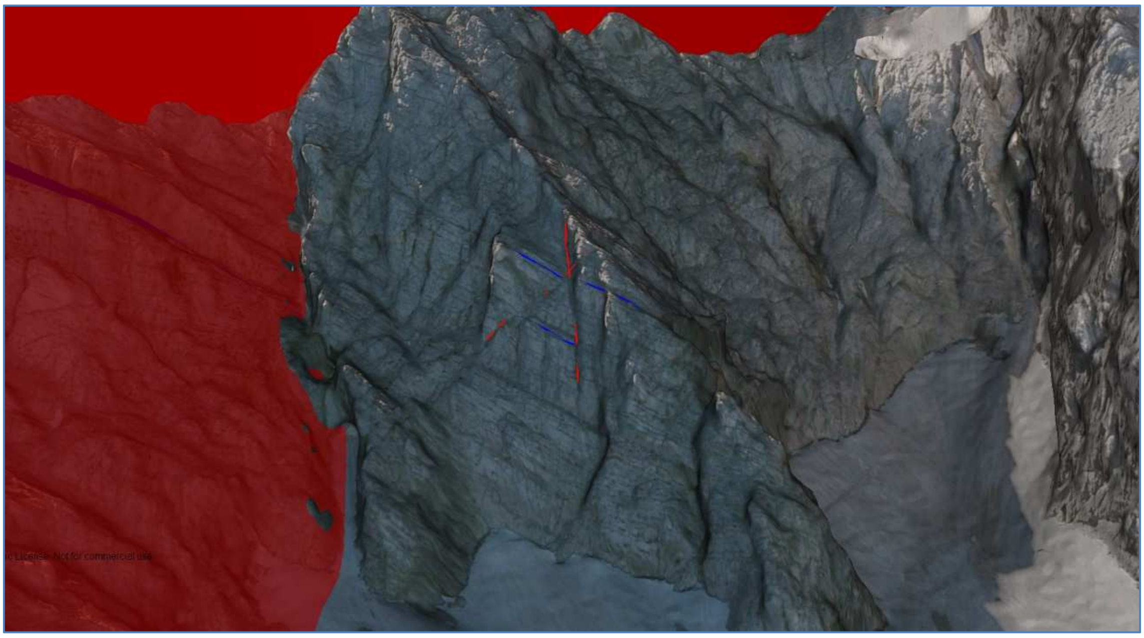


Figure 2: Small-scale pre-tilt conjugate normal faults interpreted from the photogrammetric model in MVE Move software. Cliff height is ~150 m.

Our work demonstrates that vertical aerial photographs routinely acquired by national survey authorities can be successfully used to generate textured surface models of barren rugged mountainous terrain, which can be cost- and time-effectively used for rapid structural interpretation and mapping, particularly when they are complemented by field measurements and observations.

Acknowledgements: We thank Midland Valley Exploration Ltd. for supplying us free licenses of Move software through their academic licensing program. Aerial photographs used in the study were kindly provided by the Surveying and Mapping Authority of the Republic of Slovenia. Academic license of PhotoScan software is made available at significantly reduced price by Agisoft LLC.

Suitability of terrestrial lidar and digital photogrammetry for surveying and analysis of fold structures

Bianca Wagner* & Bernd Leiss

Geoscience Centre, University of Göttingen, Goldschmidtstr. 3, D-37077 Göttingen, Germany; bwagner1@gwdg.de

Key words: *terrestrial lidar, photogrammetry, fold geometry, fold analysis.*

Quantitative fold structure analyses at different scales are essential for deducing deformation mechanisms and the reconstruction of the deformation history of orogens. However, not only the field surveying of fold structures, especially in view of their quantification in three dimensions with the classical tools as measuring tape, grid mapping with measuring tapes, geological compass, field book and camera is a time-consuming and laborious job, but also the construction of a georeferenced 3D model of fold structures based on classical data.

Another crucial aspect of the classical field surveying of folds is the limitation by poor outcrop conditions. Reasons might be restricted or no accessibility due to high outcrop walls, water or fences, limited visibility because of vegetation, difficult measurability due to very smooth walls or complexity as a result of irregular outcrop walls or distant outcrops. Furthermore, inappropriate oriented outcrop surfaces in respect to the fold geometry can make a survey even worse.

Over the past years, modern 3D surveying techniques like terrestrial lidar and digital photogrammetry became progressively affordable for geological fieldwork and now start to complement or replace traditional methods. We started to utilize these techniques on fold structure surveying and to apply quantitative fold structure analysis on different outcrop settings in Central Germany. Different workflows were developed and tested to optimize data conversion, handling and representation.

We applied a laser scanner and a single lens reflex camera, complemented by a differential GPS device and laser tachymeter. Data conversion, correction and analysis were done by means of different free as well as commercial software packages. To test different outcrop situations, different quarries, salt mines and steep cliffs, exposing from single fold to complex folds in limestone, greywacke, cherts, rock salt or potassium salt, were selected.

As a result, exact 3D point clouds of all exposed folds could be generated by the use of both techniques. The resultant point clouds are suited as excellent visualisation objects as well as base for accurate geometrical measurements in the range of mm or cm of single and complex folds. In addition, the point clouds serve as input dataset for the construction of detailed geological 3D models comprising punctual, linear and plane fold elements.

In summary, terrestrial lidar and digital photogrammetry are excellent field techniques to survey and document exposed folds in the range of few meters to tens of meters, especially under poor outcrop conditions. Different fold sections can now easily be correlated in 3D space to construct complete fold structures with their 3D fold geometry. Certain fold elements, e.g. axial planes, can be reconstructed much faster and much more accurate compared to the classical approach. The only limiting factors are the very large datasets and the processing power.

As next steps, we seek (1) to involve drones for completing datasets from inaccessible areas and perspectives and (2) to incorporate 3D microfabric analysis data in the fold models as e.g. grain shape and crystallographic preferred orientations to better understand strain paths and deformation mechanisms.

Use of terrestrial laser scanning data in monitoring anthropogenic objects and landscape elements

Janina Zaczek-Peplinska* & Maria E. Kowalska

Warsaw University of Technology, Faculty of Geodesy and Cartography; jzaczek@gik.pw.edu.pl

Key words: *terrestrial laser scanning, surface evaluation, deformations, shifts.*

Laser scanning has become one of the basic tools in mass movement research (JABOYEDOFF *et al*., 2012). Data from laser scanning is applicable in geomorphology (JABOYEDOFF *et al*., 2012), hydrology (MILAN, 2009), forestry (ALBERTI *et al*., 2013), archaeology, hydraulic engineering and geodetic engineering (ZACZEK-PEPLINSKA *et al*., 2014). It is worth noting that when surveying surfaces, glacier movement, landslides or engineering objects both terrestrial laser scanning (TLS) and airborne laser scanning (ALS) are used.

Geometric comparison of TLS point clouds registered in different time periods is a multifaceted task which requires bringing the data to a common coordinate system and proper selection of the input point clouds. Factors such as point distribution, dependent on the distance between the scanner and the surveyed surface, angle of incidence, required scan density and intensity value, have to be taken into consideration. Quality and accuracy assessment of analysed data from periodic measurements obtained through TLS in the form of point clouds is a prerequisite for running a correct analysis. Uniform measurement precision on the whole analysed object and uniform (or close to uniform) distribution of points on the surveyed surface are necessary in order to maintain high reliability of the results. Due to complexity of the mentioned factors, as well as the characteristics of carried out measurements and properties of scanning instrument it is impossible to obtain a reproducible, uniform cloud.

Results of surface deformation analyses of two objects are presented below: anthropogenic – a concrete water dam – and natural – the front of a glacier. Despite completely different characteristics of the two, in both cases similar methods of statistical and geometric analysis and intensity image classification methods were used. This underlines universality and broad range of possible application of the used solutions.

Fig. 1 presents a superimposition of an image in reflected laser beam's intensity value colour range of an area of a concrete dam's downstream wall (impounded water level above 40 m), map of point distances from a fitted plane presented in colour range and a photography of the analysed test area. The presented superimposition shows that when assessing the condition of a surface one should make use of information from various sources. Using interdisciplinary source data analysis as a base it is possible to classify what type of treatment the surface should be subjected to. By analysing the intensity image one obtains information of surface staining (blue colour) and the existing seepage (red colour). A map presenting point distances from a fitted plane provides surface information on possible deformations (cavities, protrusions), whereas photography allows for visual verification of the results.

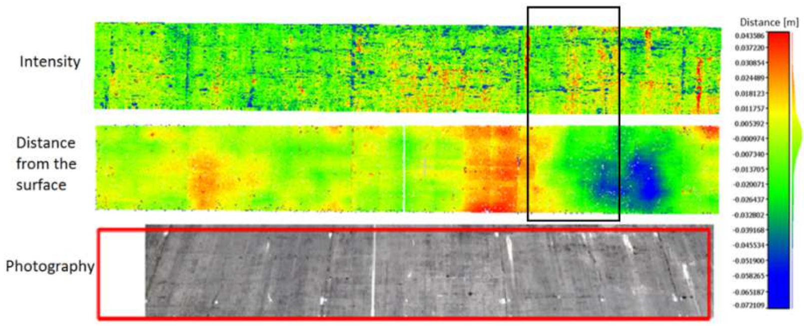


Figure 1: Superimposition of intensity image, map of point distances from a fitted average plane presented in colour range and a photography of the analysed wall area.

A selected area of the intensity image and deformation map is highlighted in Fig. 1, in black. By analysing a smaller area and by selecting an individual colour range for it a better, more detailed information is obtained on the area in question. When analysing the whole selected area, it is not possible to detect a crack which is clearly visible when a proper scale is chosen for the fragment. Through detailed analysis of the distance map it is possible to notice that in the central part of the crack a concavity exists that is not visible on intensity image.

As previously mentioned, terrestrial laser scanning is also applicable in glaciology, such as in monitoring glacier cliff changes, ranges or movement. Glacier monitoring is particularly important when they are present in close vicinity of settlements or locations for which gaps leading to ice calving pose a great threat (GODONE *et al.*, 2012).

Study of glacier range changes is also important due to global warming. On the basis of glacier cliff measurements, it is possible to determine warming dynamic and its main areas. Data from scanning can also be used in a number of exposed ice analyses, examples of which are presented below.

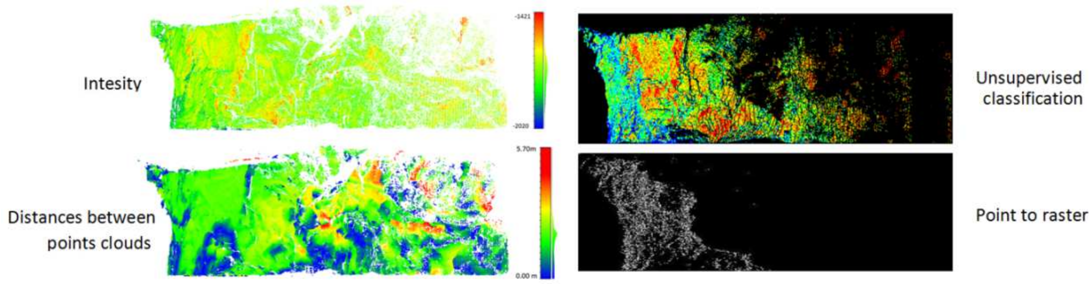


Figure 2: Picture components present in order: [Intensity] – image of the analysed fragment of Ekologia glacier's front surface on King George Island (Antarctica) presented in reflected the laser beam's intensity colour range. The image presents the state of the glacier after calving, which took place before the second control measurement. [Distances between point clouds] – Colour map presenting distances between scans taken at an interval of two weeks, the most widespread changes (red colour). [Unsupervised classification] – the results of unsupervised classification using an ISODATA method with parameters: 6 classes, threshold coefficient 0.99, 25 iterations. [Raster to point] – presents raster visualisation of a scan fragment with raster size 0.25 × 0.25 m.

The superimposition presented in Fig. 2, similarly to the previous example, presents how data processed and visualised in different ways is complementary. By analysing the intensity image one obtains information on areas of dirty, old snow (yellow and red colour) that remained unchanged. A map of point distances between the scans provides surface information on possible shifts of the glacier's front and glacier cliff deformation (cavities, protrusions, gaps) between consecutive measurement periods.

In summary, terrestrial laser scanning technique allows for fast registration of geometry and spectral properties of various objects and surfaces. It can be used to monitor processes occurring in space and time with millimetre accuracy. Specialised, modern software makes it possible to filter, transform and merge registered point clouds, generate spatial models and then process the obtained data – creating cross sections, layers and projections. This provides a wide range of research possibilities and identifying dynamic of changes occurring in time.

Acknowledgments: The authors thank Dr Marcin Rajner, Sławomir Łapiński and Mariusz Pasik for granting access to the data from scanning of Ekologia glacier and Prof. Katarzyna Osińska-Skotak for help in performing classification of intensity images (Warsaw University of Technology, Faculty of Geodesy and Cartography).

References

ALBERTI, G., BOSCUTTI, F., PIROTTI, F., BERTACCO, C. & DE SIMON G., 2013. A LiDAR-based approach for a multi-purpose characterization of Alpine forests: An Italian case study. *IForest*, 6: 156-168.

GODONE, D. & GODONE, F. 2012. The support of geomatics in glacier monitoring: the contribution of terrestrial laser scanner, In: J. APOLINAR MUNOZ RODRIGUEZ (Ed.), *Laser Scanner Technology*, InTech. doi:10.5772/33463.

JABOYEDOFF, M., OPPIKOFER, T., ABBELAN A., DERRON, M-H. & LOYE, A., 2012. Use of LiDAR in landslide investigations: a review. *Natural Hazards*, 61(1): 5-28.

MILAN, D., 2009. Terrestrial laser scan-derived topographic and roughness data for hydraulic modelling of gravel-bed rivers. In: G.L. HERITAGE, A.R.G. LARGE (Eds.), *Laser Scanning for the Environmental Sciences*, Wiley-Blackwell: 133-146.

ZACZEK-PEPLINSKA, J., OSIŃSKA-SKOTAK, K., WUJANZ, D., & KOŁAKOWSKA, M., 2014. Analysis of the possibility for using the results of terrestrial laser scanning (TLS) measurements and classification algorithms of images for the engineering structure surface condition assessment. *Proceedings of the 1st Vertical Geology Conference*, University of Lausanne, 227–232.

Integrating UAV-based photogrammetry to improve digital outcrop model quality

Ruisong Zhou[1*], James L. Best[1], Christopher Stohr[2], Arjan Reesink[1] & James R. Damico[2]

[1] Department of Geology, University of Illinois at Urbana-Champaign, IL, USA; rszhou@illinois.edu
[2] Illinois State Geological Survey, Champaign, IL, USA

Key words: *photogrammetry, UAV, outcrop, geocellular model,* CO_2 *sequestration.*

Geological carbon sequestration is one of the most promising strategies to significantly reduce the level of CO_2 concentration in the atmosphere. Planning for CO_2 sequestration requires modelling flow of injected CO_2 in a geological formation. It is important to precisely build a geocellular model of the storage formation. Structure from motion (SfM) photogrammetry allows the collection of three-dimensional (3D) topographic datasets that can be used to create 3D digital models of an outcrop. Unmanned aerial vehicles (UAVs) allows better coverage of outcrop exposure at locations inaccessible by common photogrammetry techniques. Integrating UAV-based photogrammetry in a digital outcrop model construction enhances data acquisition and processing, thus improving the model quality. A digital study, based on a photogrammetric SfM dataset acquired using both UAV and handheld camera, was carried out to investigate outcrops of the Lamotte Sandstone Formation, Missouri, which is an analogue for part of the lower Mt. Simon Formation, the main CO_2 storage reservoir in Decatur, Illinois.

The aim of this study was to improve the quality of digital outcrop models, thus generating better geocellular models. Examples of outcrops from Hickory Canyon area were used to highlight its geology features and build the geocellular model. This study primarily includes: 1) considerations of the major factors affecting the quality of the photogrammetric datasets, and the optimization methods needed to obtain good digital elevation models, and (2) quantifying the length and thickness of the principal sedimentary structures (cross-sets) and how they are stacked within the outcrop. Heterogeneity at various scales can be determined for target reservoirs by outcrop analogues. The cross-set thickness of fluvial sandstones can be used to infer the dimensions of larger-scale geological features, such as unit bars, compound bars, and channel belt width and depth.

From these high-resolution and high accuracy outcrop models, geological features were extracted, which can be used to build geocellular models comparable to those built using subsurface data, allowing direct comparison between the Lamotte outcrop and the lower Mt. Simon.

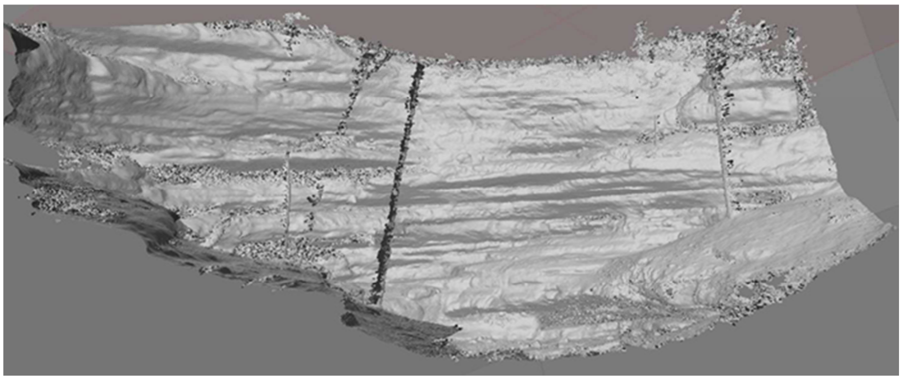


Figure 1: Photorealistic image texture outcrop model acquired using drone.

Notes

Notes

Notes

Notes

Virtual Outcrop Geology Group
Uni Research AS
P.O. Box 7810
N-5020 Bergen, Norway

ISBN 978-82-8361-004-8 (print)
ISBN 978-82-8361-005-5 (pdf)