WILLIAM SMITH MEETING 2021

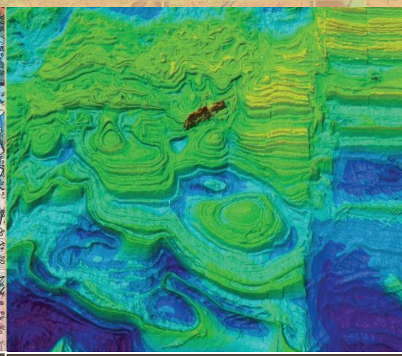
Geological mapping: of our world and others

V I R T U A L   C O N F E R E N C E

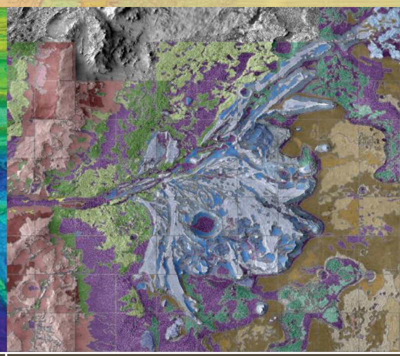
Abstract Book

19-21 October 2021

Geological Survey of Scotland, 1892



Weymouth Bay, Bosence *et al* 2018



Jezero Crater, Mars, NASA JPL

#wsmith21

2021 YEAR OF SPACE

William Smith Virtual Meeting: Geological Mapping - of our world and others

19-21 October 2021

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William Smith Virtual Meeting 19-21 October 2021

Geological Mapping - of our world and others

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We would like to thank **Imaged Reality** for their support

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Please find further information here.

Day One
Session One

Introductory remarks

John Dewey

University College, High Street, Oxford OX1 4BH

Geological mapping is the central basis of geology from the thin section (Marion Holness) to whole planet (Haxby, Sandwell) scale. Mapping is the determination of the 2D or 3D distribution of rock types, the boundaries and their nature and attitudes between them. It is mostly performed in the field where the petrography, bedding and way-up in sedimentary rock, structures such as foliation and lineation, fracture patterns and anything may be observed in outcrop. in areas of poor exposure, changes of slope, vegetation, spring lines, field geophysics, and hand-auguring are useful tools. I map mostly at 1/10,000 (6” scale); mapping in Tibet in 1985 at 100,000 was a terrible shock. Large scale patterns and boundaries may be discerned from satellite-based remote sensing but cannot achieve the detail to do anything useful. I recognise the value and efficiency of tablet mapping (Terry Pavlis) but I am happier with paper maps augmented by air photos and satellite imagery (Google Earth, Zoom and Apple) with drawing film overlays in a weather-proof map-case. In mountain areas and in regions with few features on base maps, GPS is indispensable. Boreholes, drilling, mines and deeper surveys such as COCORP, BIRPS and EARTHSCOPE extends geological maps into the vertical dimension but the pixel size is vastly greater in outcrop. I have no prescription for making a geologic map; each person has their own methods. All that is necessary is great detail, keen observation, precision and accuracy, showing precisely the positions and shape of outcrops (green-lining), and the massive pleasure of being in the field, watching the map grow, and developing an increasing understanding of the area of concern. Compilations always ultimately depend on field mapping. As Kevin Burke said “nothing much can be done in geology without a map.”

Field safety is critical which is mainly common sense but students must be trained in geo-bush-craft. In my youth, when field safety was rarely mentioned, I have put myself into a number of dangerous situations that could have ended badly. Several friends have been killed. Field mapping is not risk-free but mapping alone in a remote and challenging terrain is always taking a serious risk even with a satellite phone.

Mapping as a key to understanding the evolution of major strike-slip faults during Cenozoic hyper-oblique collision between India and SE Asia

Christopher Keith Morley

PTT Exploration

Mike Searle (Oxford University), Sarawute Chantraprasert (PTT Exploration and Production), Kwanjai Chenoll (PTT Exploration and Production)

Regions around major strike-slip faults bounding the West Burma Terrane (WBT) within the hyper-oblique, Cenozoic collision zone between India and SE Asia, are mapped in highly variable detail. Jungle, no-go areas, remoteness, and the Andaman sea act to conceal the geology, while regions of gem mining, urbanization, hydrocarbon exploration, and satellite images offer high resolution insights. Fault patterns are identified from diverse map types including: geological, seismicity, seismic hazard, gravity, magnetics, depth to Moho, GPS, satellite, DEM, radiometric ages, seismic reflection-derived horizons and attributes, side scan sonar. On the east WBT margin is the c. 1700 km-long dextral Sagaing Fault, which accommodates c. 50% of 3.6 cm/yr northwards relative plate motion between India and SE Asia. Regionally, the southern Sagaing Fault in the Andaman Sea is a transform fault in a back-arc pull-apart basin, while in the north the fault passes into the Eastern Himalayan Syntaxis. Fundamental information about the fault, in part derived from fault patterns, (e.g. timing/magnitude of displacement, interaction with other major faults in the region, Kabaw Fault, Yunnan region) remains controversial. In the Minwun Ranges satellite data from a remote region on the western strand of the northern splays in the Sagaing Fault suggests a syn-kinematic Oligocene-age basin developed above a releasing bend listric normal fault detached on ophiolite-related serpentinites. Field mapping in the Mogok area, revealed the most complete section of lower/middle crust in SE Asia, which was exhumed east of the Sagaing Fault, and indicates <20 Ma for fault initiation. Offshore, in the Gulf of Mottama, the sedimentary response to strike-slip motion is of latest Miocene-Recent age. Early fault maps suggested a large-scale fault termination horsetail pattern. However, recent mapping indicates an unusual combination of delta-related gravity-driven growth faults, partially decoupled from underlying strike-slip deformation. Eocene-Early Miocene palaeogeographic reconstructions of the WBT and Andaman Sea are highly varied. Recent palaeomagnetic based paleogeographic reconstructions with an Eocene-age eastern WBT transform margin seem reasonable at a small map scale. Yet evidence for a transform fault is lacking on large-scale maps (seismic reflection data) of the Andaman Sea. Mapping of the Sagaing Fault zone has both improved understanding of structural styles, palaeogeography, fault timing and evolution and highlighted gaps in our understanding.

Geological mapping of Southern Thailand in the 1960s, and the place of SE Asia in Gondwana: a historical review

Michael Ridd

retired, formerly BP

Geological mapping of Southern Thailand in the 1960s, and the place of SE Asia in Gondwana: a historical review

In the 1960s, anticipating the award of offshore concessions in the Gulf of Thailand, BP decided to carry out reconnaissance geological mapping over the whole of Southern and Southeastern Thailand including its Gulf islands, a total area of about 100,000 square kilometres. Until then the only coverage of that region was the geological map of Thailand at a scale of 1:2,500,000, published in 1951 (Brown et al). The result of BP's mapping was a series of eight maps at 1:250,000 scale that were integrated into the new Department of Mineral Resources 1:1million scale geologial map of Thailand (Javanaphet et al. 1969), and are the subject of this paper. The mapping provided a data-base that underpinned discussions of Thailand's place in Southeast Asian plate-tectonic reconstructions that were beginning to emerge at that time. In particular, new light was thrown on the Phuket Group, a very thick Upper Palaeozoic diamictite-bearing succession apparently sourced in the west, a region now occupied by the Indian Ocean. That in turn suggested a possible Gondwana origin for Southeast Asia (Ridd 1971, 1980). Other findings included the nature of the Khlong Marui Fault belt that marks the boundary between terranes having very different stratigraphic successions. Close to the Cambodian border the island of Ko Chang was found not to be Upper Mesozoic Khorat Group red-beds as mapped in 1951, but to be a centre of acid volcanism that pre-dated the Khorat Group. The emphasis of field mapping these days is on obtaining detailed data which necessarily means over areas of limited extent. But a very broad regional mapping project such as BP's in Thailand did reveal stratigraphic and tectonic insights that arguably could be revealed only from a wide-ranging regional study of this kind.

The tectonic evolution of Anglesey and adjacent mainland North Wales: accretion of peri-Gondwanan elements in the UK sector of Iapetus

Graham, A Leslie

British Geological Survey

Wilby, P.R (British Geological Survey), Dartnell, R (School of Geography), Kendall, R.S (British Geological Survey)

Edward Greenly’s geological map of the island of Anglesey (Ynys Môn) was published by the Geological Survey of England and Wales in 1920; that original work, and the memoir that accompanied the map, is now a century old. After a period of new BGS fieldwork, we can now showcase a 2020 edition of the geological map of Anglesey – one that builds upon the primary observations and insights of Greenly, as well as our own targeted field surveys aimed at testing specific geological relationships in a modern scientific framework. As a result, we are able to present a new tectono-stratigraphic synthesis for Anglesey and adjacent parts of NW Wales, that reveals a comprehensive record of Wilson Cycle processes in the UK sector of the Appalachian-Caledonian Orogen. Terrane elements now identified in Anglesey and NW Wales amalgamated first of all on the peri-Gondwanan margin in the Cambrian, before rotational translation across Iapetus in the Ordovician and subsequent, highly oblique accretion and amalgamation onto the Laurentian margin in the Silurian. In Anglesey, we identify elements of Late Neoproterozoic accretion forming the pre-Appalachian basement; Cambrian extension, deposition and continental margin growth; Early Ordovician accretion and renewed extension; transfer and rotation across Iapetus; and finally, terminal Caledonian collision and continental foreland basin development. The new BGS map and the accompanying tectono-stratigraphy have been designed to deliver this complex geological record, and the understanding that lies behind the map/model, to the widest possible geological community.

Session Two

Approaches and legacy of geological mapping by William Smith – a dip into history.

Owen R. Green

University of Oxford

William Smith (1769-1839) is admired by the geological community as the architect of the first geological map of England, Wales and parts of Scotland, published in 1815. However, Smith never titled himself 'a geological map maker', although in his limited published works he describes himself as an engineer, a land or mineral surveyor, a land drainer, and a mineralogist. From the earliest days of observing the strata around Bath, Smith was developing the technique of 'ground truthing', demonstrating this to friends the Rev. Joseph Townsend and the Rev. Benjamin Richardson. Coupled with his bio-stratigraphical observations while working for the Somerset Canal Company Smith dictated his 'Order of Strata' in 1799, setting a benchmark in defining stratigraphical horizons through the fossil assemblage contained within them. Recognising the importance of Nicholas Steno's 1699 'law of superposition', Smith established two principles of stratigraphy: (1) the Principle of Superposition states that newer beds will lie on top of older unless the succession has been overturned, causing it to be reversed. This may result from either folding or thrust faulting; (2) the Law of Strata identified by fossils states that each distinct bed (or group of beds) in the succession contains a distinctive fossil assemblage. This law allows beds belonging to the same stratum to be correlated over a geographical area. Both teachers and students recognise that understanding and using these principles is essential in constructing a geological map. In constructing his geological map, a task which occupied Smith for the first 15 years of the 19th century, he recognised that to realistically display the surface expression of the different strata his map would have to accommodate the natural topography.

Finding a suitable 'base map' was a contributing factor in the delay in publication of his geological map. John Carey the London based cartographer and map engraver undertook the task. The accuracy of these provided Smith with the confidence to construct cross sections in 1819, enabling a 3-D interpretation from his 2-D map. Another fundamental principle exploited by field mappers today. His brilliance as a geological map maker was initially not recognised by contemporaries. However, in the Oxfordshire village of his birth, Churchill, the 3rd Earl of Ducie (1827-1921) had erected the splendid three tired 4.5m high monument in 1891. Ducie's connection to the village was through his marriage to the daughter of the local MP James Langston who owned and lived in Sarsden House (the Manor House for Churchill), and upon his death bequeathed the house to his only daughter Julia. Ducie visited the island of Malta in 1852-53, and produced a geological map of the islands, eventually published in 1870. Inspiration for the map may have come from learning of Smith's legacy.

Developing the ground model and updating the geological map for the A417 'Missing Link', Cotswolds, UK

Lee Taylor

Arup / Terrafirma

Dan Raynor (Arup), Iolo Ellis (Arup), Cheran Bhogal (Arup), Edward Boss (Arup), David Boon (British Geological Survey), Mark Shaw (Highways England)

Upgrades to a 5.5km section of the A417 near Birdlip to a dual carriageway are proposed to improve road safety and support economic development of the wider area. The scheme vision is for a landscape-led highways improvement scheme that will deliver a safe and resilient free-flowing road whilst conserving and enhancing the special character of the Cotswolds AONB. The scheme runs from the base of the Cotswold Jurassic Escarpment, rising up to the Cotswolds Plateau, and includes the full geological sequence of the area. This paper describes the work undertaken to develop the ground model used for preliminary design, building on the desk study work and ground investigation scoping undertaken by Mott MacDonald Sweco JV during an earlier stage of the project. Works included specification of ground investigation (GI), terrain analysis, geological and geomorphological mapping, and interpretation of the geophysical and intrusive GI results.

The preliminary assessments of ground risk were undertaken by ground engineers from Arup in close consultation with Highways England's Geotechnical Advisor for the scheme. The British Geological Survey were appointed to provide detailed stratigraphical logging and assist with an updated stratigraphical framework for the scheme area, based on the investigations undertaken. The intrusive GI was undertaken by Geotechnical Engineering Ltd and geophysical investigations by Terradat, with management by Osbourne. A GIS geodatabase developed for the scheme allowed for accurate visualisation of the various data sets and preparation of interpretative maps.

The three-dimensional modelling software, Leapfrog Works was used to help visualise and understand the data in three-dimensions. These tools will allow the ground model and ground risks to be effectively communicated and managed into the detailed design stage. Updates to the geological mapping proposed as part of the development of the ground model are described. These include amendments to geological boundaries, outcrop positions, fault locations, and inclusion of newly identified faults. Terrain analysis has informed the development of a detailed geomorphological map for the mass movement deposits within the escarpment slopes. This has been used to characterise and better understand the historic and potential slope movement mechanisms, therefore informing the geotechnical risk management for the scheme.

Lithological map of Metripolitan France 1/50 000

Anne Bialkowski

BRGM, French Geological Survey, Georessources Division

Bernachot Isabelle (BRGM), Chêne Frédéric (BRGM)

The cartographic geological data available at a scale of 1 :50,000 have been reworked to overcome stratigraphic age. The first original geological maps available at 1/50,000 have been harmonized in the 2010's to cover each departement from metropolitain France. Each map is associated to a database, that contains among others informations related to lithology. The lithological map was produced from these data. The lithological informations contain in the harmonized maps preserved all the details and are hierarchized. Theses maps mainly display bedrock deposits, and also superfcial deposits, only when represented on the original maps.

To succeed in this classification, we use a new lexicon that describe lithological information, an elementary building block of an Information System reference plateform. The initial information is broken down into three stages or « levels » which constitue the classification or hierarchy. Three levels are identified, from the main rocks families to sub-classes, and a fourth additionnal level is labelled as a « componant » in order to preserve the entire lithological description.

On the same method, a new legend was built. The colour and the symbols are indexed by the three lithological levels. Indeed, the graphic representation offers a quick look and a also a practical mapping. The project was initiated in 2019, continued in 2020 with the integration of three new harmonized departements and a V1 version is expected by the end of 2021, designed to evolved, soon available on our website viewer. Concept evolution, data structuration, and harmonized lexicon make it possible to provide information more accessible to a wider audience, ti meet the need of geoscientists from applied geosciences such as landuse planning, risk management or the underground water reservoir characterization.

Multiscale geological mapping of the autochthonous regolith in Metropolitan France: history, issues and methods

Florence Quesnel

BRGM (French Geological Survey)

Frédéric Lacquement (BRGM), Caroline Ricordel-Prognon (BRGM), Hélène Tissoux (BRGM), Yaël Guyomard (SGNC), Aurélien Leynet (BRGM), Aurore Hertout (BRGM), Frédéric Chêne (BRGM), Isabelle Bernachot (BRGM), Anne Bialkowski (BRGM)

The BRGM defines the autochthonous regolith as the in situ meteoric weathering profiles of all ages affecting all geological substrates, whereas the allochthonous regolith corresponds to terrestrial (aeolian, glacial, fluvial, palustrine, lacustrine, colluvial, slope…) sediments. Weathering profiles are sometimes fossilized by younger strata and possibly subsequently exhumed or sometimes long remaining exposed and polyphased. Their evolution is a function of the parent rocks' lithology, as well as topography and tectonic, sea level or climatic variations. Their representation in geological maps is recent in France, while in UK regular geological mapping has long been carried out in two-sheets (regolith and solid geology) and in Australia geologists have been studying such alterites for over a hundred years, because they concentrate major mineral resources. However, the need for knowledge about the weathering profiles grows with many other societal issues, including those related to the effects of climate change: land use planning, agronomy, forestry, natural hazards, environment, water resources...

Crucial information is lacking about the occurrence, geometry, lithologies and physico-chemical properties of the different horizons constituting the alloterites and isalterites in weathering profiles, in particular the mineralogy of the clay assemblages and the degree of the transformations from the parent rocks. The critical zone is also very often associated with isalterites, which are never mapped, although present almost everywhere. Examples of geological maps and 3D models will be presented, particularly in the Paris Basin and adjacent basements. Developed since the 1990s in France from various data, at scales ranging from 1:10,000 to 1:1,000,000, they may involve integrated studies, upscaling or contours generalization tests.

The geological objects and the working methods will be illustrated, as adapted to the studies' objectives and tending towards a homogenized approach within the framework of the 'Référentiel Géologique de la France' (RGF). Data quality, amount and spatial distribution are essential for producing reliable maps. This necessarily requires to establish a robust typology, conditioned by the understanding of i) the processes behind the various weathering profiles' types, ii) their links with the evolution of correlative reliefs and basins, and by the reconstruction of the stages and timing of their development.

A new geological data model for the Geological Survey of Austria

Mathias Steinbichler

Geological Survey of Austria

Bayer Isabella (Geological Survey of Austria), Schuster Ralf (Geological Survey of Austria)

All data models follow the goal to abstract the reality of things as good as possible for a certain purpose. For geological data the abstraction process is challenging and therefore different models were created according to the view on geology of different geologist. Nevertheless, standardisation is a big task at the Geological Survey of Austria. Here we want to present a new geological data model for Austria. This model is the outcome of ongoing discussion through the last years and is now applied to newly created data as well as old data, which are tried to be transformed into the new model. The most outstanding feature of this new model is the use of a multi-layer approach. The base-layer is seamless and represents rock units assigned to tectonic units. As the outcropping of this base-layer is limited in the field a lot of geological interpretation using structural geology, drillings, etc. has to be applied. In some regions in Austria, it is quite hard to get a well interpreted seamless base-layer, nevertheless this is essential for possible further derivations of 3D - 4D models, and generalised small-scale maps/datasets . On top of the "hard rocks in tectonic units" layer several more layers are intended in the model. Amongst them are rocks associated to basins, Quaternary deposits, geomorphology, structural geology and tectonics. In combination with other standardisation tools (e.g. nomenclatures of geological units) we try to meet the requirements of a modern geological service for Europe as well as for the regional geological history and characteristics. This contribution will give an impression of the data model itself and a recently created map using this model.

Session Three

KEYNOTE: The future of Geospatial Information for the UK

Karen Hanghøj

British Geological Survey

Geoscience information in the form of maps and models have always been intrinsically linked to wider forms of geospatial data, evidenced by the BGS's original incarnation in 1835 as a department of the Ordnance Survey. Current trends in BGS research highlight growing integration of geoscience data and knowledge with increasingly diverse forms of geospatial information to deliver decision-support tools as well as new forms of forecasting and subsurface environmental monitoring. The integration of geological data, maps and models with diverse geospatial data is essential to underpin effective response and adaptation to environmental challenges, inform policy, and enable industry. To realise this potential, geospatial data must be available and accessible to decision makers in government and industry, and to academia. The BGS, in conjunction with the UK Government's Geospatial Commission, is working to make all its data more findable, accessible, interoperable and reusable following the FAIR principles. By doing this we are investing in a shift from informing towards enabling stakeholders as well as stimulating innovation. The need to share data and knowledge does not stop at the UK's border. Creating, curating and distributing geoscience data requires the development of efficient knowledge infrastructures, processes which are increasingly been undertaken through international networks. The growth of data sharing and increasing data accessibility will bring real opportunities, but also challenges. Alongside legal responsibilities and ethical questions there is a funding dilemma: in a world where authoritative geospatial information is seen as central to the advancement of society we need to address the dichotomy of increasing open access while raising investment.

GMAP: Planetary Geologic Mapping within the Europlanet Research Infrastructure

Angelo Pio Rossi

Jacobs University Bremen

Matteo Massironi (Universita' di Padova), Andrea Nass (DLR), Monica Pondrelli (Universita' d'Annunzio), Luca Penasa (INAF), Riccardo Pozzobon (INAF), Carolyn van der Bogert (University of Muenster), Carlos Brandt (JacobsUni), Giacomo Nodjoumi (JacobsUni),

Geologic mapping is a key component of any geoscientific study of Solar System bodies. Institutional and systematic efforts on planetary geologic mapping are historically led by USGS, while research-focused mapping is widespread in the community, as well as and in scholarly publications, although often just as part of the iconography. GMAP (Geologic MApping of Planetary bodies) is an activity of the Europlanet H2024 Research Infrastructure (https://www.europlanet-gmap.eu) aimed at supporting European planetary geologic mapping efforts, through standards, data services, tools, documentation, and community training and engagement, as well as mapping product dissemination and publishing (e.g. Naß et al., 2021; Pondrelli et al., 2021). Heritage from the recently concluded H2020 Space Planmap project (https://planmap.eu) is present within GMAP. The focus of Planmap was on developing innovative geologic mapping products, and its scientific and technical heritage is being used and further developed within GMAP. In addition, tools and data services are available and being developed. Training activities for the community started with the 2021 Winter School (https://www.planetarymapping.eu), and follow-up schools, courses and workshops are going to be held throughout the duration of the Research Infrastructure (see also Rossi et al., 2021). Open Source tools developed or maintained within the GMAP infrastructure are made available (see Penasa et al., 2020). Individual mapping projects at any level of maturity (conceived, started, published) are welcome to become GMAP community mapping projects, and their results made discoverable and usable by the community. The infrastructure also supports sharing and reuse of geologic mapping data and basemaps. GMAP is part of Europlanet 2024 RI and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871149. References: Naß, et al., (2021) Planetary Geologic MAppers 2021, LPI contrib. no. 2610, #2610. Penasa, L., et al. (2020) EPSC2020-1057, https://doi.org/10.5194/epsc2020-1057 Pondrelli, M., et al. (2021) Planetary Geologic Mappers 2021, LPI contrib no. 2610, #7007 Rossi A. P., et al. (2021) 5th PDW/PSIDA birds-of-a-feather on geologic mapping https://aprossi.github.io/planetdata2021/

Geological mapping and the making of Europe: Inventing a common subsurface?

Leo Corbel

SAGE Research Unit (CNRS/ University of Strasbourg)

The idea to map the geology of continental Europe is very old. It was born in 1881 during the second International Geological Congress among a group of European geologists who created the Commission de la Carte Géologique du Monde (CCGM). For almost a century, many European geologists passed through this learned society, whose cartographic project had a pan-European federative vocation. Although the project was badly affected by the tragedies of the 20th century, the geological mapping of Europe experienced an unexpected revival with the European construction. With the increase in the price of raw materials in the 1970s, the European Commission became interested in the resources that could be found in European subsurface. In the early 1980s, the Commission funded the member states' Geological Surveys to carry out gitological mapping of Europe. The common scientific policy provided funding and political legitimacy for new geological mapping of Europe. The rapprochement between geological surveys in European common scientific policy also owes much to the voluntarism of the surveys' directors, many of whom had been through the CCGM and were imbued with a shared European feeling. At the end of the 1980s, the European geological surveys launched a new geochemical mapping project at European scale. Since the establishment of a representative office of the European geological surveys in 1996, geological mapping projects in Europe became more numerous and diversified. These projects, bringing together European geological surveys, concern fields as varied as mineral raw materials, seabed, geothermal energy, hydrogeology, and more recently critical raw materials. Furthermore, mapping initiatives have gone hand in hand with the creation of a pan-European geological database combining data historically gathered by national geological surveys as well as data collected through European projects. The genesis of a pan-European database within the framework of the European Union enables the creation of a technical and political artefact that the geologists of the CCGM could only have dreamed of a century ago: a common European subsurface.

The International Quaternary Map of Europe: Cooperation without political boundaries

Kristine Asch

Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, BGR)

The International Quaternary Map of Europe and Adjacent Areas (IQUAME 2500) is a major European geological GIS mapping project being managed and implemented by the German Federal Institute for Geosciences and Natural Resources (BGR) under the umbrella/auspices of the Commission for the Geological Map of the World (CGMW) and the INQUA (International Union for Quaternary Science). It is a collaborative European project that involves to-date 43 national geological survey organisations and is supported by a network of scientific advisors. The aims of the project are to develop a web-enabled pan-European Geographic Information System (GIS) containing up-to-date harmonised data of the European Quaternary geology, on- and offshore. The map data will be made accessible via a web map application. Geology does not know political boundaries. Thus, a particular challenge in projects like this is finding and harmonising the optimal actual data and information from all European and adjacent countries on- and off-shore. This encompasses the correlation of classifications, e.g. the Quaternary stratigraphy from the Iberian Peninsula to Turkey, from Greenland to Russia. Also all other information needs to be described coherently, and will be harmonized semantically and geometrically in cooperation with the participating national experts, and finally displayed as (digital) map layers in a structured, readable, understandable and also optically harmonious way, as William Smith did it with his famous geological map of England, Wales and parts of Scotland in 1815. The IQUAME will be including information on stratigraphy and lithology of the European Quaternary map units, the maximal extension of the main European glaciations, genetic descriptions of the Quaternary deposits and rocks, active faults and key localities such as geological and anthropological sites of interest. Ultimately, the IQUAME 2500 will set the Quaternary geology of the whole of Europe in a coherent context, and show the actual status of Quaternary mapping and research in Europe in order to enhance the understanding of the complex and unique Quaternary geology of the continent.

Session Four

KEYNOTE: Rocks Are Us: 179 years of geological mapping, technological innovation and scientific advancement by the Geological Survey of Canada

Marc St-Onge

Geological Survey of Canada

Mapping the geology of Canada is an immense and challenging task, with Canada having the second largest land area (after Russia), the longest coastline of any nation, an extensive continental shelf, and a geological history that spans over four billion years. In pursuit of this task, fieldwork has taken the Geological Survey of Canada (GSC) to the farthest frontiers of this huge country, with the early history of the GSC closely aligned with the growth of Canada. The mapping odyssey began in 1842 with its first Director, Sir William Logan, conducting fieldwork in the southern Canadian Shield, the St. Lawrence Lowlands, and the Canadian Appalachians. Following Confederation in 1867, the GSC's mapping efforts focused on the western half of the new Dominion, specifically the Western Canada Sedimentary Basin and the Canadian Cordillera. At the end of World War II, it was determined that only 11% of Canada had been adequately mapped in the first 100 years of the Survey. Fortunately, in the early 1950s, three technological innovations drastically changed the nature of fieldwork: bush planes mounted on pontoons or tundra tires, the commercialization of helicopters, and public availability of aerial imagery. Over the next two decades, the GSC successfully deployed twenty-nine large-scale helicopter-supported operations to complete the first-order geological coverage of Canada's remote sub-Arctic and Arctic regions. Work since the mid-1970s has focused on fundamental tectonic questions with geological mapping leading to several noteworthy discoveries. These include: (1) the oldest rocks in the world (Acasta); (2) the 'suspect terranes' of the Canadian Cordillera; (3) the world's most-complete Precambrian ophiolite (Purtuniq); (4) one of the oldest low thermal gradient eclogites (Kovik); and (5) the applicability of Himalayan tectonic concepts to Proterozoic orogenic belts (e.g. Wopmay, Trans-Hudson, Grenville). Where does the Survey go from here? Approximately 55% of the Canadian Arctic remains insufficiently mapped to fully constrain its complex tectonic history or to provide 21st C stakeholders with a complete digital geological database. The way forward seems clear: more fieldwork and more strikes and dips.

Modern 1:100 000 scale mapping of northern Baffin Island, Nunavut, Canada: structural insights on the evolution of the Rae Craton and NE Trans-Hudson Orogen

Benoit Saumur

Université du Québec à Montréal

Skipton, D.R. (Yukon Geological Survey); Johnston, S.T. (University of Alberta); Wodicka, N. (Geological Survey of Canada); Folkesson, C.-P. (Université du Québec à Montréal); St-Onge, M.R. (Geological Survey of Canada)

Compared to other regions of Canada's Arctic, the geology of northern Baffin Island has received little attention since the completion of reconnaissance mapping in the late 1960s. The area is vital for our understanding of the tectonic history of the Archean Rae Craton in both Canada and Greenland. It includes economically significant greenstone belts (Mary River Group) containing the banded iron formations that host the high-grade, large-tonnage Mary River iron deposit at Canada's currently northernmost mine. Recent helicopter-supported mapping campaigns, integrated with previous mapping, geochronological, remote sensing and geophysical datasets, reveal that northern Baffin Island is dominated by Mesoarchean felsic orthogneiss and Neoarchean monzogranitic to granodioritic plutons. Meso-Neoarchean greenstone belts are preserved as strongly deformed 1-50 km-scale panels bounded by the plutonic and gneissic units, and are less extensive than implied by previous reconnaissance-scale maps. Among numerous new findings stemming from the latest field work, structural analysis of greenstone belts within the crustal-scale Paleoproterozoic Isortoq shear zone provides new insights on the involvement of the Rae Craton in the broader ~1.8 Ga Trans-Hudson Orogen. The Isortoq Shear Zone and two associated greenstone belts (Isortoq and Eqe Bay) form part of a SSE-verging nappe reminiscent of the S-verging Rinkian nappes in West Greenland. The NE-striking, moderately SE-dipping Isortoq belt is structurally-thinned, metamorphosed, sheared and overturned, whereas the ENE-striking, steeply-dipping Eqe Bay belt is structurally thickened, less metamorphosed, less sheared, and shows right-way-up polarity. Both greenstone belts are folded around a hinge zone to the SW, forming an asymmetric synformal anticline. Our findings imply that S-verging tectonics – opposed to and pre-dating the dominantly N-verging nappes of the Foxe Fold Belt on central Baffin Island – are greater in spatial extent than previously considered, and emphasize the importance of horizontal transport via nappe tectonics during assembly of the Nuna Supercontinent.

Mapping the oblique - looking back at the last 50 years of photogeological map making in Greenland

Erik Vest Sørensen

Geological Survey of Denmark and Greenland

Photogeological mapping as a tool for geological map making in Greenland have developed enormously since the early pioneer work of Lauge Koch in the 1920´ties. In the following, a 50-years historical overview of the key technological landmarks that helped shape the present-day geological map-making workflow at the Geological Survey of Denmark and Greenland survey is presented and followed by a description of the present-day mapping set-up. Early use of systematic photogeology in the geological map making (1:100.000) date back to the work of Gilroy Henderson in 1962 who pioneered geological map making at the survey through his mapping of the alpine Uummannaq district using just a simple stereoscope. A more systematic use of photogrammetry was initialized in the mid 70´s as a long series of mapping experiments by Keld S. Dueholm and co-workers, including the Amik system that combined a mirror stereoscope with a computer. The experiments were conducted in cooperation with the technical University of Denmark and eventually led to the establishment of the Photogeological Laboratory at the survey in 1977. The laboratory was first equipped with a KERN PG2 stereoplotter which for many years served well in the systematic mapping of Greenland. Despite the technological development, the rugged topography of the Greenlandic landscape posed a specific challenge due to the lack of resolving power on steep cliff phases within traditional nadir looking aerial photographs. This sparked the development of what in the early 90´ties was called multi-model photogrammetry which allowed the operator to combined vertical aerial photographs with a series of stereo-models taken from handheld small-frame cameras. The system, located at the technical University of Denmark, consisted of a fully computer-controlled KERN-DSR11 analytical plotter. This was a major technological landmark which allowed the geologist to map and quantify the geology of the often near vertical cliffs in three dimensions and it has been fundamental to the mapping and understanding of the Nuussuaq basin in west Greenland. Nowadays, we are in the era of digital photogrammetry, where bulky analytical plotters haven been exchanged with digital photogrammetric workstations and analogue cameras have become digital while archive imagery has been digitally scanned. Now stereo-images acquired using handheld cameras are collected on a routine basis during field work. This has led to a rapid increase in size of our image archive, which for the Ummannaq district originally mapped in 1962 now is covered by 35.000 images. Adding the adjacent area further to the north this sums up the coverage to about 60.000 images. This large image archive is now fundamental to the current geological map sheet production.

Standing on the shoulders of giants: using historical mapping, reconnaissance fieldwork and photogrammetry to create modern, low-cost geological maps of the Prøven Igneous Complex, West Greenland

Ken McCaffrey

Durham University

P.R. Sleath (Durham University, GEUS, now Aberdeen University), J. Grocott, (Durham University), T.F. Kokfield (GEUS), E.V. Sørensen (GEUS)

Producing geological maps of high-grade basement terrains in remote regions has always been technically and logistically challenging hence expensive and time consuming. For these reasons, geological maps of some parts of Greenland remain unpublished and the geology of these regions is understudied and resource potential under constrained. New 1:100,000 scale maps are in production by GEUS (Geological Survey of Denmark and Greenland) covering parts of the Rinkian Fold Thrust Belt, a Paleoproterozoic orogenic belt on the edge of the Rae Craton in western Greenland. Here, we focus on the northern part of the orogenic belt that includes the 1.87-1.9 Ga Prøven Igneous Complex (PIC), a c. 90 x 80 km orthopyroxene-bearing monzogranite to quartz monzonite intrusion (charnockite) that underlies most of two new map sheets. The new maps were generated rapidly (2-3 years work) because we were able to combine GEUS archived map data, reconnaissance fieldwork and 3D digital mapping methods. Superb original mapping at 1:40,000 scale between 1967-79 by T.C.R. Pulvertaft, O. Stecher & J. C. Escher (GEUS) (the Giants whose shoulders we stood on) was reinterpreted in a modern tectonic framework. A GEUS field team took over 40,000 high-definition images of the impressive fjord sides from a helicopter. Structural data and samples for geochronology and geochemistry were collected at ground-stops guided by the archive maps to constrain tectonic models. Photogrammetry analysis was completed as part of an MSc study (P. Sleath) on the photography dataset using 3D Stereo Blend software at the Photogeological Laboratory at GEUS. Detailed mapping established a tectonostratigraphic sequence of orthogneiss, paragneiss, layered and massive charnockite that enabled us to place the structural history of the PIC in a regional framework. Together with geochemistry and geochronology, the new maps constrain Paleoproterozoic plate configurations and we now suggest the Rinkian foreland lay to the east under the present-day Greenland ice sheet and a subduction boundary existed to the west in what has become Baffin Bay.

Mega-fold interference patterns in West Greenland: mapping from air and ground of the structural architecture of deep Archean crust

Brian Windley

University of Leicester

The near-total exposure in West Greenland enabled exceptionally detailed mapping, by aerial photos, helicopters, boats and on foot, of lithologies and structures by members of the Geological Survey of Greenland (GGU) now GEUS at 1:20,000-1:50,000 scales and detailed structures at 1:200 scale. The Mesoarchean craton of Greenland comprises predominant TTG gneisses and layers up to 2 km-thick and 90 km-long of metavolcanic amphibolites and layered-graded anorthosite-leucogabbro-gabbro-UM complexes (from magma chambers of island arcs). In spite of being folded isoclinally three times (within interference patterns up to 5200 km2) and metamorphosed to granulite and amphibolite facies, undeformed lithologies and structures are often beautifully preserved enabling meaningful mineralogy, geochemical-isotopic analyses, and zircon dating. Examples will be illustrated with maps and 3D constructions from three regions of triple-folded interference patterns at metre-scale; thrust-imbricated, km-wide, calc-alkaline metavolcanic arc belts; hydrothermally altered volcanic rocks; sedimentary structures in chromitites, anorthosites and UM rocks; sapphirine-bearing lithologies with up to 60 minerals; unique isoclinal exhumation anticlines in anorthosites; successive structures in an Archean subduction-exhumation channel, and regional mapping of lithologies using only inclusions in gneisses. Integration of these data allows reliable interpretations of individual units and a robust holistic model for the craton. The tectonic evolution (as opposed to crustal evolution) of Archean deep crust can only be worked out by detailed mapping at all scales.

Day Two

Session Five

The myth of the Highland Cretaceous revealed by the art of palaeogeographic mapping - a synthesis of 250 years of collaborative science

David I.M. Macdonald

School of Geosciences, University of Aberdeen

Since the term was coined in 1873, palaeogeography has provided a powerful map-based tool for synthesising, visualising, and testing diverse regional data. A palaeogeographic mapping approach can be brought to bear on the Scottish Highlands, where there are still unsolved problems despite two and a half centuries of geological investigation. The Highlands were one of the cradles of geological investigation and mapping, providing some of the earliest evidence for deep time, the igneous origin of granites, mechanisms of intrusion, and lateral displacement of rocks in the crust. They are better mapped and more studied than almost any other ancient orogen, yet two related questions remain. First, has the topography of this mountain belt been preserved for more than 400 million years, and if so, how? Second, what is the origin of the geomorphic surfaces in the Highlands and how and when did they form? In particular, the 2,000' (610 m) surface has been variously ascribed to marine peneplanation of Cretaceous, Paleogene, or Neogene age, suggesting relatively recent uplift of the Highland block. This view has also been partially supported by some fission track (AFT) and other thermochronology studies. Contrary views have been expressed by a number of authors using a variety of approaches: facies analysis of late Mesozoic outcrops, principally in the Western Isles, stepwise palaeogeographic mapping of onshore and (more recently) offshore deposits, and seismic investigation of onlap patterns in the North Sea and West of Shetland basins. Work on sediment routing systems and source to sink analysis over the past two decades also supports the idea of long-lived topography. These studies can all be interpreted as showing the persistence of a stubborn, elevated Highland terrane since the end of the Caledonian Orogeny. This paper reviews the changing methodology of palaeogeographic mapping from 1873 to the present, focusing of the depiction of the Scottish Highlands. It also examines the feedback between new field evidence from geologic mapping and the evolution of palaeogeographic ideas for the Highlands. The conclusion of this study is that the Highland topography is indeed ancient.

Geological map of the Rinkian fold and thrust belt (Palaeoproterozoic, West Greenland)

Pierpaolo Guarnieri

GEUS, Geological Survey of Denmark and Greenland

Nigel Baker (GEUS), Diogo Rosa (GEUS), Erik V. Sørensen (GEUS)

The Rinkian fold and thrust belt lies to the north of the Nagssugtoqidian orogen in West Greenland between latitudes 69°30´N and 75°N. North of Nuussuaq it is characterised by the presence of a several kilometers thick Palaeoproterozoic sedimentary succession, the Karrat Group, which overlies and is interfolded with Archaean gneisses and supracrustal rocks. The Paleoproterozoic Karrat Group of West Greenland hosts one of the few deposits that have been mined in Greenland, the Black Angel Zn-Pb mine. However, a study of the whole extent of the Karrat Group has not been carried out since it was first mapped in the 1960s. The fieldwork program, which took place between 2015 and 2017, aimed at contributing towards the evaluation of the mineral potential of the Karrat Group, through an updated and integrated approach, supporting a detailed understanding of the mineral system(s). During three ship-based field seasons fully supported by a helicopter, the entire Karrat area was flown for the acquisition of oblique photos for 3D-photogeology and most of it was covered by new field mapping, observations and ground control. The collected geochronology, stratigraphy, geochemistry, structural geology and economic geology data, together with 3D-photogeology, improved the understanding of the complex tectonic evolution of the region, and has allowed the revision of the stratigraphy and lastly the production of three new geological maps of the area at 1:100.000 scale: Maarmorilik, Nugaastsiaq and Pannertooq map sheets. Together with the GEUS map series production, there will be also a web-GIS version of the geological maps will also be published.

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Mapping of superimposed faulting in poly-orogenic contexts. Variscan and Alpine faults in Duje Valley (Picos de Europa, Cantabrian Mountains, NW Spain)

Brais Gonzalo-Guerra

Instituto Geológico y Minero de España (IGME, CSIC). Unidad de Oviedo. C/ Matemático Pedrayes 25, 33005, Oviedo, Spain.

N. Heredia (Instituto Geológico y Minero de España (IGME, CSIC). Unidad de Oviedo. C/ Matemático Pedrayes 25, 33005, Oviedo, Spain); J. García-Sansegundo (Universidad de Oviedo, Departamento de Geología, C /Jesús Arias de Velasco s/n, 33005 Oviedo, Spain)

A new geological map of the Duje river valley (Picos de Europa, Cantabrian Mountains, NW of Spain) has been elaborated. This map has enabled the study of structures related to Variscan and Alpine orogenic cycles and their crosscutting-reactivation relationships. Four superimposed fault sets have been defined, based on geometrical, kinematical and deformational criteria as well as crosscutting and tectonic-sedimentation relationships, which have been drawn out from field, map and cross-section evidences. A connection between the structural fault sets and four genetic fault populations has been established, therefore defining: Variscan thrusts, Late-Variscan faults, Permian-Mesozoic faults, and Cenozoic Alpine reverse faults. Clusters of the already mentioned structures form several fault systems of each type, whereby deformation has affected the rock massif through several tectonic events. Furthermore, interrelations between genetic fault populations have been studied, coming up with 15 possible reactivation scenarios, of which 12 have been acknowledged in the study area. The geometrical features of previous discontinuities generated in the different tectonic events have been noticed to drive later propagation of the subsequent deformation events. The aim of this study is double: (i) to improve Variscan and post-Variscan structure understanding, as well as the complexity and variability of their reactivations through the Alpine orogenic cycle and (ii) to develop a new methodology for displaying and mapping multi-deformation structures that have been active in several orogenic cycles, improving their interpretation. Acknowledgements This study has been supported by the FALPINO project of the Spanish I+D+i Plan (CGL-2015-70970-P) and two predoctoral “Severo Ochoa” grants, provided by Principado de Asturias autonomic government (BP19-001 and BP19-148).

From ophiolite obduction to post orogenic extension: Using mapping to understand the Aegean Orogeny and metamorphic core complexes

Thomas Lamont

University of Bristol

Michael Searle (University of Oxford)

Rocks from the Cycladic Islands in southern Greece preserve a complete cycle of mountain building associated with the collision between Greater Adria and Eurasia followed by orogenic collapse. Despite decades of work that has focussed on the structural evolution of the metamorphic core complexes and the low-angle normal faults that accommodated regional Aegean extension, there remains a very limited understanding of the pre-extensional evolution of the area. To fully constrain the tectonic and metamorphic framework of the Cyclades prior to extension requires a thorough understanding of the metamorphic fabrics and isograds, cross-cutting relations, and relative timing of different compressional and extensional structures. Geological mapping is a fundamental tool used to collect and interpret such key data. Six years of mapping the islands of Tinos, Syros and Naxos, and contemporaneous petrological and geochronological investigations, have confirmed the Aegean Orogeny fits into a typical Tethyan-type orogenic cycle associated with a NE dipping subduction zone that accommodated the closure of an ocean over a time period from ca. 74-11 Ma. Our mapping has shown the Aegean Orogeny represents a sequence of SW verging thrust sheets that, from structurally high to low, record: i) Ophiolite obduction recorded by the Tsiknias Ophiolite on Tinos which formed at ca. 162 Ma in a suprasubduction zone setting and was obducted towards the SW together with a sub-ophiolitic metamorphic sole that attained P–T conditions ca. 0.8 GPa and >750 °C at ca. 74 Ma. ii) Oceanic subduction and attempted continental subduction which resulted in high-pressure metamorphism of the Cycladic Blueschist Unit, that reached ca. 2.3 GPa and 560 °C at 53-46 Ma. iii) Subsequent crustal thickening resulted in Barrovian metamorphism and kyanite-sillimanite grade conditions on Naxos of ca. 1.0 GPa and 700-730 °C at ca. 20-14 Ma, and was associated with isothermal decompression and muscovite dehydration melting forming S-type leucogranites. iv) A change in stress regime resulting in the development of low-angle normal faults that cross-cut the earlier collisional and ‘extensional shear’ fabrics contemporaneous with intrusion of I-type granites at ca. 15-11 Ma derived from melting of lower crust granulite facies metamorphic rocks, possibly associated with heating during orogenic collapse. v) An even younger phase of E-W shortening which steeply refolds the low-angle normal faults and core complex rocks.

A new generation of geological maps : the event-geological maps. Example of the Pyrenees orogen (France)

Maxime Padel

BRGM

B. Le Bayon (BRGM), F. Cagnard (BRGM), B. Issautier (BRGM), T. Baudin (BRGM), C. Prognon (BRGM), H. Tissoux (BRGM), F. Lacquement (BRGM), S. Grataloup (BRGM), A. Hertout (BRGM)

The new digital information technologies can overcome the limitations imposed by the classical graphical representation of geological maps. During the RGF research project ("French Geological referential"), we developed a new concept of geological map, which integrates the different elements of a rock's description according to the chronological order of appearance. The geological history of a rock or a geological object results from a succession of distinct geological events successive over time. The RGF event-geological map includes a time line that allows to show the different stages recorded by a geological object from its formation to its current state. We present a first version of the event-geological maps of the Pyrenees orogen (France). To produce these maps, we integrated 3,400 geological events (referenced into a lexicon : the Geological Event Referential) in more than 120,000 polygons coming from 60 french geological maps at 1: 50,000 scale. The geological history of the Pyrenees will be presented through different event-geological maps, at key ages, produced through the Geological Event Referential. Recent advances and innovative scientific results obtained during the project will be presented with the different event-geological maps. Such innovative geological event-maps, allow to generate cartographic products with various geoscientific data sets, at different time and space scales, for different themes and issues.

Geologic mapping of the Northern Apennines nappe stack on the Isle of Elba (Italy): a correlation between surface geology and exploration boreholes

Samuele Papeschi

Kochi (X-Star), JAMSTEC, Japan

Eric Ryan (NTNU, Norway), Giovanni Musumeci (Università di Pisa, Italy), Francesco Mazzarini (INGV, Pisa, Italy), Paolo Stefano Garofalo (University of Bologna, Italy), Giulio Viola (University of Bologna, Italy)

The eastern Isle of Elba exposes the complete nappe stack of the Northern Apennines belt in the hinterland sector of the belt. The study area is characterized by an apparently simple W-dipping monocline of E-verging nappes, which developed during Oligocene-Miocene thrusting and the subsequent tectonics of the Northern Tyrrhenian Sea. We developed a geologic map of Eastern Elba at 1:5’000 scale based on field mapping, structural analysis, and the re-interpretation of private borehole logs, acquired for exploration purposes in the ‘50s. Some of these logs reach depths of 500 m below the sea level, allowing for the first time the reconstruction of the deep architecture of the island. We integrated mesoscale data of the outcropping formations with the petrographic and microstructural analysis of samples and available metamorphic and geochronological constraints. The resulting map documents the architecture of thrust nappes and the relationships between deformation, magmatism, metamorphism, and ore forming processes. Based on this extensive dataset, we show that such an apparently simple monocline of nappes recorded an E-vergent polyphase tectonic history including (1) Oligocene – early Miocene thrusting and exhumation of tectonic units, (2) syn-orogenic extension and out-of-sequence thrusting, culminating with (3) the late Miocene interaction between thrusting and emplacement of granitoids. Post-magmatic thrusting led to the final coupling of HP-LT and LP-HT units in the nappe stack, producing a complex architecture of the thrust wedge that resulted from multiple stages of in-sequence and out-of-sequence thrusting accompanied by folding and low-angle normal faulting. We also document for the first time the N-dipping character of the Zuccale Fault, representing the youngest (late Miocene – early Pliocene) large-scale structure developed in the study area.

Session Six

Mapping deformation: the map representation of geological structure

Paul Marwick

Knowing Earth Limited

Douglas Paton (TectonKnow Limited)

Faults and folds are the clearest expression of deformation we can observe directly in the rock record. But the map representation of these structural elements has only developed over the last 100 years, and even today, there is still some ambiguity in symbology. And yet, we take map representation of structures for granted. We ‘know’ what we are looking at. But what is a structural map? A structural map is the cartographic representation of folds, faults, and lineaments. But, we need to recognize the distinction between the trace of a structural feature (e.g. a line representing a fold axis) and its 3D expression (form). For much of the 19th century, the structure was implicitly visualised through outcrop patterns with no explicit map symbolisation. But over the last century, a structural map has increasingly come to mean a map of lines (or sometimes polygons), each with a symbology representing different kinematics. We then translate this into the 3D structural form, either in our head or using software. Today we have Geographic Information Systems (GIS) to store and visualise spatial data and various powerful desktop software to interrogate the 2D and 3D expression of mapped structures. But the fundamental challenges are the same. What do these mapped structures represent? What is the kinematic story they tell us? How reliable are our interpretations and map representations? Are our maps and databases appropriate to the problem we want to solve? In this talk, we will address these challenges in two ways. First, by considering the history of structural mapping going back to the first map representations by De La Beche in the early 19th century, the formalisation of mapping symbology initiated at the USGS by John Wesley Powell in the 1870s, and the subsequent development of a complete symbology set by the USGS during the 20th century. Second, by using a suite of new digital tectonic databases collectively named Reclus, which we have developed as a baseline resource to investigate crustal architecture and geodynamic evolution. These databases are underpinned by a robust data management system and comprehensive audit trail – this is essential where digital data is to be analysed using AI (Artificial Intelligence) algorithms. By linking the power of spatial databases with a clear map representation, we have a powerful tool for better understanding Earth dynamics. But we need first to understand what those structural maps represent.

The Austrian national fault database and the pan-European HIKE fault database: The interplay of structured data with Linked Data – challenges and opportunities

Esther Hintersberger

Geological Survey of Austria (GBA)

Ch. Iglseder (GBA), B. Huet (GBA), M. Schiegl (GBA), R. Van Ede (TNO), S. Van Gessel (TNO)

European geology has been studied for almost two centuries and the results have been published in numerous geological maps at different scales. Knowledge of the movement along major fault systems is the key for understanding the tectonic evolution in such a complex environment as Europe. Besides being a typical product of geological mapping and a necessary part of kinematic models, faults are prominent features defining resources (e.g. minerals, thermal conduits) and/or inducing potential hazard to subsurface drilling, injection and extraction activities (e.g. conventional hydrocarbon extraction in Groningen, Netherlands). Furthermore, the knowledge on faults, their subsurface geometry and deformation history has also increased in complexity, eventually showing the limits of printed maps for adequately representing the current state of knowledge. Therefore, collecting and structuring the available information on faults and presenting it in a harmonized and generally accessible way across national borders is a necessary challenge for geologists and geodata providers. In this contribution, we present two new fault databases, the national Austrian and the European HIKE fault databases, in order to illustrate the challenges and opportunities of each approach.

The national and scale-independent fault database of Austria focuses on the kinematic information available on faults and shear zones, which is the most important aspect of understanding faults in the national context. In order to capture the variety of geological environments and the highly varying levels of available data, the European HIKE fault database combines three different aspects of a fault object: fault geometry, kinematic attributes and a linked semantic vocabulary where non-structured information can be stored.
As the European HIKE fault database took inspiration from the Austrian fault database, both share several aspects. In addition to structured information stored in attribute tables, both databases contain a hierarchical classification scheme, which sorts faults and shear zones into groups of local, regional or transregional relevance through a semantic vocabulary of named faults. The vocabulary that has been generated under the principles of Linked Data, which allows storing unstructured information such as geographic description, detailed investigation history, debated theories etc., but also creates a network beyond the actual fault database by including links to other existing fault databases and additional information, e.g. Wikipedia or other semantic vocabularies. With the both examples presented here, we show that a balanced mix of structured information stored in attribute tables and an associated semantic vocabulary provides geologists the opportunity to share complex geodynamic and kinematic information.

The European fault database was developed during the Horizon 2020 GeoERA projekt HIKE and contains data from Geological Survey Organizations in Austria (GBA), the Netherlands (TNO), Germany (BGR, LfU, LAGB, LBGR), Belgium (RBINS-GSB), Iceland (ISOR), Denmark (GEUS), Poland (PIG-PIB), Lithuania (LGT), Italy (ISPRA), France (BRGM), Ukraine (GEOINFORM), Portugal (LNEG), Slovenia (GeoZS), Albania (AGS) and

the Pannonian Basin Area (MBFSZ). The GeoERA HIKE project has received funding from the European Union's Horizon 2020 research and innovation programme under agreement No. 731166.

A multiscale characterization of fault and fracture networks in granite: outcrop analogues for deep geoenergy applications

Gianluca Amicarelli

Newcastle University

Mark T. Ireland (Newcastle University), Colin T. Davie (Newcastle University)

The spatial characteristics and distribution of faults and fractures are vital for understanding permeability and fluid flow within geological formations. These characteristics have implications across a broad range of geoenergy applications. Here fracture systems in granite with specific implications for radioactive waste disposal, geothermal energy, and recovery of rare earth minerals are investigated. Using the fault and fracture systems within granitic rocks of the late Caledonian Loch Doon pluton (Craignaw) in SW Scotland as an analogue, the variations in characteristics of fractures systems across multiple scales are investigated. Initial findings from a multiscale investigation using: 1) using aerial imagery for macroscale structural data collection (kilometers down to meter scale), 2) drone-based acquisition for SfM and 3) fieldwork for mesoscale investigations are presented. Comparison is made of the characteristics of fracture systems interpreted using different data collection methods, focusing on fracture length, orientation and topology. The aerial imagery has a resolution of 25cm and therefore has limitations for the characterization of fracture intersections and aperture. Measurements were made from 3D outcrop models which have a resolution of ~3cm, that have been created from structure-from-motion (SfM) photogrammetry as comparative dataset from which to investigate the characteristics of the fracture networks. Finally, traditional field sampling methods will be used to determine fracture roughness and aperture. Further work will use the detailed characterisation from the complementary datasets to statistically study the connectivity, permeability, and transport properties of the fractured rocks using discrete fracture network (DFN) models. These models will be used to investigate the relative significance of different scale fractures and the intersections, and consider the implications for hydrogeological modelling.

Mapping fractured craters and chaos on the Moon and Mars

Giacomo Nodjoumi

Jacobs University Bremen

Angelo Pio Rossi (Jacobs University Bremen), Giacomo Nodjoumi (Jacobs University Bremen), Matteo Massironi (Università degli Studi di Padova), Riccardo Pozzobon (Università degli Studi di Padova)

Geological mapping, possibly supported by multiple approaches, can shed light on the geological history of a certain region. The development of remote sensing and the acquiring of new data, allowed in the years also the characterization and mapping of planetary surfaces. Our study consisted in a detailed investigation through spectral, structural, stratigraphic and geomorphological approaches of broad regions on Mars and on the Moon, resulting in morpho-stratigraphic and structural maps. The studied regions, called chaotic terrains (Mars) and Floor-Fractured craters (FCCs) (Mars, Moon), are characterized by a basaltic bedrock disrupted into polygonal flat-topped blocks, bounded by concentric and radial faults that intersecting each other generate the characteristic mesas. The nature of the collapse that triggered the disruption has long been debated, and the detailed analyses carried on in our work to produce the morpho-stratigraphic and structural map led to the proposition of a new hypothesis on the formation mechanism: a piecemeal caldera collapse. The piecemeal caldera collapse is characterized by multiple cycles of inflation and deflation of a buried magma chamber, resulting in the collapse of the overlying brittle material and the formation of the typical polygonal blocks. As for chaotic terrains, on top of the disrupted bedrock, the occurrence of sedimentary deposits bearing hydrated minerals suggests a complex geological history even following the collapse. On the other hand, on the lunar FFCs hydrated minerals do not occur, but also in these cases the disruption is accompanied by a complex geology, with the association of pyroclastic deposits, mafic compositions, and central peaks of crustal origin. By studying the relationships between maximum displacement and length of the faults affecting FFCs, we were able to retrieve crucial information about the role played by the different lithologies and about the fault growth.

KEYNOTE: Team-based, bespoke, and machine learning: different ways to map Mars from remote sensing data.

Matt Balme

The Open University

Planetary maps, created from remote sensing data alone, can be used to build an understanding of the geology and geomorphology of a planetary body. Traditionally, systematic planetary morphostratigraphic mapping is performed by small groups of mappers to accepted standards; consistently high-quality products are produced, but maps can take years to complete.

For Mars, a wealth of imaging data facilitates geological understanding and mapping: 6 m/pixel images cover most of the planet, a few percent of the surface area has been imaged at ~25 cm/pixel resolution, and there are supporting mineralogical, thermal, and topographic data. Mapping Mars' surface is both assisted and hindered by this huge dataset: analysing these images at full resolution across large enough areas to be useful is vastly time consuming, but mapping only from lower-resolution base images missed the complexity, and more and more we can see that this complexity is vital to understanding the planet.

Here, I describe five different approaches to mapping Mars designed to achieve rapid results while utilizing full resolution data: (i) Morphostratigraphic mapping of Aram Dorsum, a landing site proposed for the ESA ExoMars mission, (ii) Large Team quad morphostratigraphic mapping of Oxia Planum, the landing site selected for the ExoMars Rover, (iii) Small team rapid morphostratigraphic mapping of ~ 1 km2 areas of Mars to simulate post-landing activity, (iv) Grid mapping of small ice-formed features across large areas of the northern plains, and (v) Machine-learning mapping of "Perceived Rover traversability" to aid landing site selection and Rover operations. Lessons learned from these studies for future mapping activities will be discussed.

Session Seven

A 1:600K Geological Map of the Sibelius Crater, Mercury

Marc Canale

Undergraduate Student, School of Physical Sciences, The Open University.

Introduction: Large scale (as opposed to quadrangle) mapping of small features on Mercury has generally only been pursued in specific association with the investigations of other features or anomalies [1, 2]. Here I present a 1:600k geological map of the 95 km crater Sibelius, with particular attention paid to impact melt ponding [3, 4], asymmetrical excavation and ejecta features, and to previous generations of impact structures that Sibelius partially overprinted. Ponding of impact melt is apparent, as well as some exceptionally large scale terrace-forming slumping. This mapping will hopefully go towards targeting areas of interest for high resolution imaging during the BepiColombo mission [5]. Data and Methods: The map is produced in QGIS 3.16.3 using data from NASA's MESSENGER Mission. I use the 166 m/pixel BDR global mosaic, the 166 m/pixel LOI (Low Incidence Angle) BDR global mosaic and the MDIS enhanced colour global mosaic, complimented by other data, namely the 8 colour MDR global mosaics (665 m/px) and a digital elevation model (DEM) that I made via the NASA AMES Stereo Pipeline. I used individual MESSENGER Narrow Angle Camera (NAC) images for investigations under a variety of illumination incidence angles. Units: Map units are mostly based on the spectral responses of surface materials. Linework is used for geomorphological features. Progress and Ongoing Work: Although nearing completion with all major units and contacts finished, some small scale surface features on the crater floor and walls are yet to be mapped. Acknowledgements: I thank for their encouragement, Prof David Rothery, Dr Jack Wright and Ben Man (The Open University), and the GMAP (Geologic MApping of Planetary bodies) group, as well as the PLANMAP Winter School (part of the EU Horizon 2020 research and innovation programme). References: [1] M. Pajola et al., Planetary and Space Science, vol. 195, p. 105136, Jan. 2021. [2] V. Galluzzi et al., Geophysical Research Letters, vol. 48, no. 5, p. e2020GL091767, 2021. [3] M. J. Beach et al., p. 1335, Mar. 2012. [4] Chapman, C. R et al. Impact cratering on Mercury. In: Solomon et al. (eds.), Mercury: The View after MESSENGER, 217–248, 2018. [5] J. Benkhoff et al., Planetary and Space Sciece, vol. 58, no. 1–2, pp. 2–20, Jan. 2010.

eologic map of the Beethoven Quadrangle (H07), Mercury.

Laura Guzzetta

INAF - Istituto di Astrofisica e Planetologia spaziali (IAPS), Rome, Italy

Lewang A. (Institut für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany), Hiesinger H. (Institut für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany), Ferranti L. (DiSTAR - Dipartimento di Scienze della Terra, dell'Ambi

Keywords: Planetary geology, Mercury, Beethoven quadrangle, Geological mapping. A new 1:3M-scale geological map of the Beethoven Quadrangle (equatorial latitude), covering an area of ~6M km2 (7,7% of the total Mercury surface), has been compiled exploiting MESSENGER data. This work is part of a global series of 1:3M-scale geological maps of Mercury, prepared in support of the ESA/JAXA BepiColombo mission to set up the context for mission operations and help re-define the mission goals. The mapping has been performed within a GIS environment and operated on a georeferenced monochromatic basemap at 166 m/pixel resolution (BDR, map-projected Basemap reduced Data Record). In support of mapping, we also used the Mercury Laser Altimeter (MLA) DTMs, several basemaps with different incidence angles, and color global mosaics. We distinguish crater materials and plains units. According to their overlapping relationships and degree of morphological preservation, craters with D>20 km and their related materials are distinguished into three morpho-stratigraphic classes (from the more degraded c1 to the freshest c3). The plains units are classified as smooth, intermediate, and intercrater plains materials (Schaber & McCauley, 1980). Based on the dominant contractional features affecting Mercury (Byrne et al., 2014), tectonics structures are interpreted as thrusts, when they show a relevant break in slope and lateral continuity or are mapped as wrinkle ridges when the break is less evident and is limited to smooth plains and basins. The SW sector of the quadrangle is floored by half of the Beethoven basin, one of the largest (D ~ 630 km) basins on Mercury of the late Tolstoian period (3.9 Ga). Similar to other large basins on the planet (e.g., Caloris and Rembrandt), we distinguished units specific to the Beethoven impact basin. Its floor is covered by volcanic smooth plains materials, and its ejecta are mapped as Brm (Beethoven rim materials), defined as hilly and radially lineated material, extending outside of the rim of the basin. The new geologic map represents a more detailed cartographic product with respect to the previously released 1:5M map of the quadrangle (King & Scott, 1990) and will contribute to improving our knowledge of the planet´s stratigraphy and surface history. Acknowledgments We gratefully acknowledge funding from the Italian Space Agency (ASI) under ASI-INAF agreement 2017-47-H.0. References Byrne P. K., Klimczak C., Şengör A.C., Solomon S.C., Watters T.R. & Hauck S.A. 2014. Mercury's global contraction much greater than earlier estimates. Nat. Geosci.,7 (4), 301–307. King J.S. & Scott D. H. 1990. Geologic Map of the Beethoven Quadrangle of Mercury. Misc. Inv. Ser., U. S. Geol. Sur., Map I-2048. Schaber G.G. & McCauley J.F. 1980. Geologic map of the Tolstoj quadrangle of Mercury. Misc. Inv. Ser., U. S. Geol. Sur., Map I-1199.

European regional-scale geological mapping of planet Mercury

Valentina Galluzzi

Istituto di Astrofisica e Planetologia Spaziali, INAF, Rome, Italy

L. Giacomini, L. Guzzetta (IAPS, INAF, Rome, Italy), D. A. Rothery. R. Lennox, C. Malliband, B. Man, D. L. Pegg, J. Wright (The Open University, UK), M. El Yazidi, G. Tognon (CISAS, Padua, Italy), L. Ferranti (DiSTAR, University of Naples "Federico II", N

A complete global series of 1:3M-scale maps of Mercury is being prepared in preparation for the forthcoming ESA/JAXA BepiColombo mission to aid selection of scientific targets and to provide context for interpretation of new data. This coordinated global geological mapping of Mercury plan exploits NASA MESSENGER Mercury Dual Imaging System (MDIS) images at the best resolution available (i.e., global average resolution of 166 m/pixel). Our mapping protocols follow the mapping standards document of the Planmap project, which are modelled closely on the USGS equivalent. Maps from H02 to H05 have already been published and others are in progress or scheduled except H01. Quadrangles H10 and H14 are completed and available in the Planmap repository. We merge the produced geologic maps together by adjusting mismatches along the quadrangle boundaries. The global merged output will be used as a digital full-scale product, which will permit detailed global or regional analyses of Mercury's surface. This project will lead to a fuller grasp of the planet's stratigraphy and surface history.

Web-based Geologic Mapping with MMGIS

Fred Calef

NASA/JPL-Caltech

Tariq Soliman [NASA/JPL-Caltech], Hallie Abarca [NASA/JPL-Caltech], Joe T. Roberts [NASA/JPL-Caltech], Amanda Chung [NASA/JPL-Caltech], Luke Dahl [NASA/JPL-Caltech]

The Multi-Mission Geographic Information System (MMGIS) is an open source, web based mapping application designed for planetary mission operations supported by the NASA Advanced Multi-Mission Operations System (AMMOS, https://github.com/NASA-AMMOS/MMGIS). MMGIS has been used to create geologic maps for two landing sites on Mars: Jezero Crater, currently being explored by the Perseverance rover, and Oxia Planum, the target for the ESA Rosalyn Franklin rover in 2022. Both science teams for the missions involved a diverse set of geoscientists, some with no mapping experience whatsoever. Our program provided a unified basemap, set of tools, and procedures to record each quadrangle assigned to different team members. Mapping scale was set according to the data resolution. Mission science teams are international by design and could take advantage of the distributed capabilities within the program to create maps, share them with other mappers, make elevation profiles, and see data in 3D to get a better sense of potential stratigraphic relationships. Drawing capabilities include making polygons, line, and points as well as annotation capabilities to record geologic units and make assessments of the terrain. By providing a standard basemap and toolset, mappers could rapidly proceed with delineating geologic units and build out the mission map. While other mapping programs are more comprehensive, MMGIS focuses on a handful of key mapping capabilities as well as providing support for Earth and other terrestrial planets (Mars, the Moon, Enceladus, etc.). By being open source, we invite collaboration from other mapping developers to expand MMGIS capabilities and add new functionality.

Geologic mapping and the search for signs of ancient life in jezero crater with NASA's perseverance rover

Kathryn Stack

Jet Propulsion Laboratory, California Institute of Technology

The Mars 2020 Science Team

The Mars 2020 Perseverance rover mission is NASA's newest flagship Mars rover, and the first mission of a potential multi-mission campaign to return samples from Mars back to Earth. Upon its successful landing in February 2021, Perseverance began an ambitious mission whose objectives are to characterize the geologic diversity and habitability of an astrobiologically-relevant ancient environment, search for signs of past life, assemble a well-documented and returnable cache of samples, and contribute to the preparation for human exploration of Mars. Perseverance's field site is located within Jezero crater, a ~50 km diameter impact crater interpreted to be a Noachian-aged lake basin inside the western edge of the Isidis impact structure. Jezero hosts remnants of one or more ancient deltas, inlet and outlet valleys, and infill deposits containing diverse carbonate, mafic, and hydrated minerals. The science return of the mission and quality of the sample cache will be maximized by a thorough understanding of the geologic context of the Perseverance landing site. To assist in building this context, the Mars 2020 Science Team conducted a collaborative effort to construct a detailed photogeologic map of the Perseverance rover landing ellipse and surrounding terrain using orbiter image and topographic data. The Science Team's photogeologic map was constructed at a 1:5000 digital map scale using a ~25 cm/pixel High Resolution Imaging Science Experiment (HiRISE) orthoimage mosaic base map and a 1 m/pixel spatial resolution HiRISE stereo digital terrain model. Mapped bedrock and surficial units were distinguished by differences in relative brightness, tone, topography, surface texture, and apparent roughness. This map is providing the Science Team a common terminology and shared understanding of the geologic units present at the Perseverance field site. The map is also forming the basis of scientific hypothesis development for strategic exploration, traverse planning, and sample caching for the Mars 2020 mission. This talk presents the Mars 2020 Science Team photogeologic map and describes how planetary geologic mapping is enhancing the science return of the mission.

Session Eight

Stratigraphic-based bedrock geologic map of the Murray formation, Gale crater, Mars along the traverse of the Curiosity rover

Christopher Fedo

University of Tennessee, Knoxville

Lauren A. Edgar (USGS Astrogeology Science Center), Alexander B. Bryk (Dept. Earth & Planetary Science, University of California, Berkeley), John P. Grotzinger (Division of Geological and Planetary Sciences, California institute of Technology), Samantha A

Given limited access to the surface of Mars, a great deal of the mapping relies on superb images and spectral inferences derived from instruments onboard orbital platforms. However, the research team of the Mars Science Laboratory mission has had the ability to directly examine ancient sedimentary rocks and stratigraphy at the ground level, using multiple instruments on the Curiosity rover. Since landing in 2012, Curiosity has traversed approximately 25 km and ascended through more than 400 m of elevation of sedimentary rocks comprising Aeolis Palus and strata exposed on the lower north slope of Aeolis Mons (Mount Sharp). Based on distinct lithologies and stratigraphic relationships, the succession has been informally divided into the Bradbury and Mount Sharp groups, the latter of which is unconformably overlain by the Siccar Point group (contains Stimson formation). Most of the stratigraphy explored using Curiosity belongs to the Murray formation (>300 m thick) of the Mount Sharp group. A core principle in building the stratigraphic column along the traverse has been to use elevation as a proxy for stratigraphic thickness because the rocks of the Bradbury and Mount Sharp groups are nearly flat lying (0-2° dip). Murray formation strata are divided into nine members based exclusively on easily recognizable lithologic attributes, as would be done on Earth. Member boundaries were initially defined along the traverse where the highest spatial resolution Mastcam and MAHLI images permitted detailed analysis. With member boundaries identified and placed on a base map created from HiRISE images (~25 cm/pixel, 1 m contour interval) acquired from orbit, member contacts were mapped laterally for hundreds of meters using HiRISE image anaglyphs, Mastcam and RMI long-distance images, and outcrop-pattern. Topographic profiles derived from orbiter laser altimetry and HiRISE stereopair images helped to identify breaks in slope linked to changes in lithology. One of the member boundary contacts could not be identified confidently along strike using this approach; that contact was extended as a computational fit using several known anchor points identified on images. Based on the mapping, strata of the Murray formation have a generally strike NE-to-E strike, with contacts mostly following contours, suggesting minimal dip; geologic cross-sections permit a dip of 0 – 2° to the north. A major finding from this geologic mapping effort is that stratigraphic, and thus, geologic contacts do not necessarily follow geomorphic contacts as mapped using orbiter images (e.g., Vera Rubin ridge). This emphasizes the importance of ground-level data in developing a geologically accurate understanding of rock units on Mars. The stratigraphic-based geologic map along Curiosity’s traverse utilizes the guiding principles of William Smith’s pioneering work by mapping the distribution of ordered, recognizable units that permit generation of meaningful cross sections. As such, Smith continues to be an inspiration and guiding light more than 200 years after publication of his seminal geologic map.

The use of mapping in selecting and characterising the ExoMars rover landing site

Peter Fawdon

The Open University

In June 2023 Rosalind Franklin, the European Space Agency's ExoMars rover, and Kazachok, the Roscosmos instrumented lander, will land at Oxia Planum on Mars. The goal of Rosalind Franklin is to search of evidence of life and it will do this by searching for physical and chemical biomarkers in the near subsurface. To sample and analyze any potential biosignatures the rover must go where they are most likely to be found. This meant choosing a landing site which both met the science criteria, a location conducive to the preservation of biosignatures located in the oldest terrains and where it would be possible for the rover to operate accessible with the entry decent and landing system. over the last 7 years we have used a variety of geological and geomorphological mapping techniques to explore Mars in preparation for the ExoMars rover mission. Starting in 2014, we used simple reconnaissance maps used to identify potential landing sites. From these initial sites we used more detailed maps that explored the geological context relevant to the rover operations. These maps develop their science case of each site and put them in a global context. More quantitative maps were also used to assess and communicate potential hazard in the sites as the number of possible sites was reduced. The Oxia Planum landing site was selected in 2018 and since then we have been using highest possible resolution mapping to characterize the 100 km long landing ellipse at a scale relevant to rover operations, identifying locations where physical and chemical biosignatures are most likely to be best preserved and accessible. To do this we drew on expertise across the ExoMars science team in a 'quad mapping' exercise and are now in the process of reconciling this to form best working hypotheses associated with each geological unit as a framework to explore during rover operations.

Evidence of aqueous alteration of layered deposits within Sera and Jiji, Mars

Ilaria Di Pietro

Dipartimento di Scienze Psicologiche, della Salute e del Territorio [DiSPuTer], Università Gabriele D'Annunzio, Chieti, Italy

G. Schmidt (GeoQuTe Lab, Roma Tre University, Rome, Italy), A. C. Tangari (Dipartimento di Scienze Psicologiche, della Salute e del Territorio [DiSPuTer], Università Gabriele D'Annunzio, Chieti, Italy), M. Pondrelli (International Research School of Plane

Martian Equatorial Layered Deposits (ELDs) are useful to reconstruct paleoclimatic and environmental setting and testify interesting and crucial aspects of ancient geological conditions. Their origin is still debated as well as the putative paleoenvironmental context in many areas on Mars (Andrews-Hanna and Lewis, 2011; Pondrelli et al., 2011; Zabrusky et al., 2012; Kite et al., 2013; Lewis and Aharonson et al., 2014; Cadieux and Kah, 2015; Annex and Lewis, 2020). To better constrain their formation and paleoenvironment, we mapped and analyzed the morphology, stratigraphy, and mineralogy within two craters in close proximity to each other in Arabia Terra, Sera and Jiji. Hydrated sulfate signatures characterize the ELDs within those craters suggesting a certain amount of aqueous activity in the past. Layer attitudes show folds with collinear axial traces trending NW – SE, whereas the analysis of layer thickness suggests shared and repeated variations from high to low energy depositional environment in both craters. The Loess Plateau China is a suitable terrestrial analog for the deposition of the ELDs in these craters. Furthermore, the existence of isolated layered mounds suggests a post-depositional process involving repeated water level fluctuations and areas of differing capillary forces. Our study contributes to the understanding of regional geological processes in Arabia Terra and reveals that a significant hydrological activity occurred in the study area, which as a result, impacts the ongoing discussion of ELD association with potential biosignatures. ACKNOWLEDGEMENTS This work has been performed within the In Time project, co-funded by the Horizon 2020 programme of the European Union (G.A. n. 823934). Data were obtained from the PDS Geoscience Node and processed using ISIS and the NASA AMES tools. REFERENCES Andrews-Hanna, J. C., and Lewis, K. W. [2011]. Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs. Journal of Geophysical Research: Planets, 116[E2]. Annex, A. M., and Lewis, K. W. [2020]. Regional Correlations in the Layered Deposits of Arabia Terra, Mars. Journal of Geophysical Research: Planets, 125[6], e2019JE006188. https://doi.org/10.1029/2019JE006188 Cadieux, S. B., and Kah, L. C. [2015]. To what extent can intracrater layered deposits that lack clear sedimentary textures be used to infer depositional environments?. Icarus, 248, 526-538. Kite, E. S., Lewis, K. W., Lamb, M. P., Newman, C. E., and Richardson, M. I. [2013]. Growth and form of the mound in Gale Crater, Mars: Slope wind enhanced erosion and transport. Geology, 41(5), 543-546. Lewis, K. W., and Aharonson, O. [2014]. Occurrence and origin of rhythmic sedimentary rocks on Mars. Journal of Geophysical Research: Planets, 119[6], 1432-1457. Pondrelli, M., Rossi, A. P., Ori, G. G., Van Gasselt, S., Praeg, D., and Ceramicola, S. [2011]. Mud volcanoes in the geologic record of Mars: The case of Firsoff crater. Earth and Planetary Science Letters, 304[3-4], 511-519. Zabrusky, K., Andrews-Hanna, J. C., and Wiseman, S. M. [2012]. Reconstructing the distribution and depositional history of the sedimentary deposits of Arabia Terra, Mars. Icarus, 220[2], 311-330.

Geological Mapping of Interior Layered Deposits Within Ophir, East Candor, and West Candor Chasmata, Valles Marineris, Mars

Josh Labrie

Brock University,Canada

Frank Fueten (Brock University), Amanda Burden (Brock University), Ariel van Patter (Brock University), Jessica Flahaut (CRPG, CNRS/UL, 54501 Vandœuvre-lès-Nancy, France), Robert Stesky (Pangaea Scientific, Brockville, Ontario, Canada), Ernst Hauber (Inst

Valles Marineris is a roughly 4000 km long network of interconnected chasmata in Mars' Tharsis region. Reaching depths of up to 11 km, these chasmata provide unique insight into Mars' crustal geology and geological history. Large, enigmatic deposits of layered material known as interior layered deposits (ILDs) can be found within many chasmata and present an opportunity to investigate some of the surficial processes that have shaped Martian geomorphology. The goal of this study is to produce geological maps of the interiors of three chasmata in central Valles Marineris: Ophir Chasma, and East and West Candor Chasmata. ILDs were categorized into distinct units based on their appearance in CTX satellite imagery, which is the only available imagery to cover each chasma in its entirety. Following the mapping of each chasm, DEMs were used to collect elevation data for the contacts between different unit types to gain a better understanding the spatial relationships between units. The results of this study show that the ILDs in these three regions share a very similar stratigraphic sequence and hence a shared geological history. The base of the stratigraphy is a massive unit which appears to be devoid of any layering in CTX imagery. The massive unit is overlain by two different layered units, the first featuring thicker layering and benches, and the second featuring thinner layering. Layered units that have been deformed by late faulting and folding appear to be near the top of the stratigraphy as do thin mesas, a late featureless cover. Work to confirm this stratigraphy is currently ongoing, and involves further mapping and mineralogical analysis.

Global Geological Mapping of Venus: Identification of Challenges and Opportunities for Future Research and Exploration

James W. Head

Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI 02912 US

Mikhail A. Ivanov, V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, Russia

Magellan global radar image/altimetry data, supplemented by Venera-15/16 images, were used with the dual stratigraphic classification approach to geological mapping to compile a global geologic map of Venus (460x106 km2; 1:10M; Ivanov, Head, 2011, PSS 59, 1559). Thirteen distinctive units, and structures/related features were identified; included were discussions of 1) the history/evolution of unit definition/characterization, 2) exploration/assessment of alternative methods/approaches, and 3) the pathway from mapping of small areas, to regional and global scales. Local/regional stratigraphic columns were compiled into a global stratigraphic column, defining rock-stratigraphic units, time-stratigraphic units, and geological time units. Superposed craters, stratigraphic relationships and impact crater parabola degradation were used to assess the geologic time represented by the column. The observed geological history could be subdivided into three distinctive phases: First, the Fortunian Period involved intense deformation and building of thicker crust (tessera). Secondly, the Guineverian Period featured distributed deformed plains, mountain belts, and regional interconnected groove belts in the first part followed by global emplacement of vast and mildly deformed plains of volcanic origin, followed by a period of global wrinkle ridge formation. Thirdly, the Atlian Period involved the formation of prominent rift zones and fields of lava flows unmodified by wrinkle ridges, often associated with large shield volcanoes and, in places, with earlier-formed coronae. About 70% of the exposed surface of Venus was resurfaced during the Guineverian and only about 16% during the Atlian. Model absolute ages suggest that the Atlian was about twice as long as the Guineverian and, thus, characterized by significantly reduced rates of volcanism and tectonism. The three major phases of activity documented in the global stratigraphy/geological map provide a basis for assessing the geological, atmospheric and geodynamical processes operating earlier in Venus history that led to the preserved record and raise a series of questions to be investigated in the coming decade: 1. Is there evidence for extensive pyroclastic activity? When, where and how abundant? 2. What is the relationship of coronae, novae, arachnoids, and shield volcanoes in space/time/altitude? 3. What constraints does the distribution/volume of different-aged volcanic plains place on atmosphere origin/evolution? 4. How does the current atmospheric environment influence the ascent/eruption of magma? 5. What is nature and relationships of festoons and pancake domes? 6. How do tessera patterns of deformation compare among different occurrences and how do similarities/differences inform us about tessera origin (e.g., lateral collision, upwelling, downwelling etc.)? 7. How much strain is represented by deformational features in tessera, and how does this vary in space/time? 8. What is the history of topography on Venus and how does this inform us about Venus thermal/geodynamic evolution? 9. What are the criteria for recognizing tectonically modified impact craters in tessera and can additional craters be recognized? 10. What are the relationships of gravity highs and recent volcanism? 11. How can we distinguish between tectonic and volcanic features and processes? 12. What is the relationship between rift zones and major lobate flows that originate there?

Day Three
Session Nine

Mapping the Ocean

Watts Tony

University of Oxford

W H F Smith (National Oceanic and Atmospheric Administration)

It has been more than 100 years since the publication of John Murray's 'bathymetrical chart' of the Atlantic Ocean. Compiled from lead-line surveys,for example those of M/V Michael Sars and HMS CHALLENGER, the contour map first revealed the Mid-Atlantic Ridge. Profiles showed, however, that apart from a few scattered islands, the deep sea floor was smooth and some what featureless, a view that persisted for the next four decades.The development of the echo sounder just prior toWorld War II dramatically altered this view, revealing deep valleys and fault offsets in the Mid-Atlantic Ridge and fractures in the flanking deep sea floor, observations that were to later lay the foundation for the development of plate tectonics. Sea floor mapping, however was challenging because of widely spacedship tracks and the irregular distribution of data. Nevertheless, Heezen & Tharpused echo so under data to construct 'physiographic diagrams' and Emery & Uchipi, Fisher and Mammerick x ,among others, contourmaps of the Atlantic, Indian and Pacific Oceans.The development of new technologies in satellite altimetry in the late 1970s and in multi beam 'swath' bathymetry in the early 1980s, together with new gridding algorithms, have greatly improved the accuracy of seafloor maps. We discuss here the accuracy and geological significance of recent grids (e.g. SRTM15 + V2.0 and GEBCO 2014, 2020) which combine echo sounder, altimetry and swath bathymetry data, along with future plans to map the entire seafloor to a resolution of 100 × 100 m or better.

Novel mapping of the INFOMAR bathymetry dataset: towards Ireland's first shallow water geomorphology atlas

Riccardo Arosio

Cork University

Riccardo Arosio[1*], Andrew J. Wheeler[1,2], Aaron Lim[1,3], Fabio Sacchetti[4], Luis A. Conti[5], Gerard Summers[1] and Thomas Furey[4]

[1] School of Biological, Earth and Environmental Sciences, University College Cork, Distillery Fields, North Mall, Cork, Ireland
[2] Irish Centre for Research in Applied Geosciences / Marine & Renewable Energy Centre, University College Cork, Cork, Ireland
[3] Green Rebel Marine, Crosshaven Boatyard, Crosshaven, Co Cork, Ireland
[4] Marine Institute, Rinville, Oranmore, Co. Galway, Ireland
[5] Escola de Artes Ciências e Humanidades, Universidade de São Paulo, São Paulo, Brazil
*rarosio@ucc.ie

Since 1996, Ireland has undertaken one of the most ambitious seabed mapping programme in the world.
Thanks to the Irish National Seabed Survey (INSS 2003-2006) and INFOMAR programmes (2006-2026), to date over 700,000 km² (80%) of the seafloor within the Irish designated area has been surveyed in high resolution. While a great deal of work has been already achieved, the quality of the data and modern mapping techniques now offer a significant opportunity to develop a standard Irish mapping approach, and the most detailed and comprehensive geomorphological map of the Irish continental shelf. The outcome of this work has the potential to benefit policy makers and industry (e.g. offshore renewables, marine spatial planning) as well as raising awareness of the marine environment to the tax payer.

We propose to test a number of existing GIS-based mapping tools (e.g. Benthic Terrain Modeller[1], GRASS geomorphons[2] etc.) in order to determine and develop a suitable geomorphic mapping protocol for the vast Irish shallow water area. Due to the shear amount of data, particular focus will be given to semi-automated and automated segmentation and classification approaches, also testing the hermeneutic limits of modern machine-based mapping in geomorphology (given that geomorphometric descriptors will be ultimately insufficient to define a landform in a full geomorphological sense). The key outcomes of this project will be the development of GIS layers and a shallow water Atlas of the Irish Quaternary and Holocene geomorphology, highlighting key seabed features in shallow Irish waters (<200 m). All the products will be freely available and integrated within the INFOMAR and the Irish Marine Atlas, for the benefit of future marine scientist, governmental agencies, industry and the general public.

[1] Walbridge, S.; Slocum, N.; Pobuda, M. and Wright, D.J. (2018) Benthic Terrain Modeler (BTM) 3.0, tools for understanding and classifying the benthic environment. [Software]. Redlands, CA, Esri. [Full details and description :Geosciences 8: 94, 24pp. DOI:10.3390/geosciences8030094]
[2] Jasiewicz, J., Stepinski, T., 2013, Geomorphons - a pattern recognition approach to classification and mapping of landforms, Geomorphology, vol. 182, 147-156 (DOI: 10.1016/j.geomorph.2012.11.005)

Geological mapping reveals the role of Early Jurassic rift architecture in the dispersal of calciturbidites: New insights from the Central and Northern Apennines

Angelo Cipriani

Servizio Geologico d'Italia - ISPRA. Via Vitaliano Brancati 48-60, 00144 Roma.

Martina Caratelli (CONICET - Instituto de Investigación en Paleobiología y Geología, Universidad Nacional de Río Negro, Av. Roca, 1242, General Roca, Río Negro, Argentina); Massimo Santantonio (Dipartimento di Scienze della Terra, "Sapienza" Università di

Geological field mapping of ancient carbonate rift-basin successions, taking advantage of a multidisciplinary approach which encompasses sedimentology, biostratigraphy and structural geology, is pivotal for reconstructing the interplay between depositional dynamics and syn-sedimentary tectonics in carbonate platform/basin systems. An outstanding example is offered by the Meso-Cenozoic Lazio-Abruzzo Carbonate Platform/Umbria-Marche-Sabina Basin system in Central and Northern Apennines (Italy). Starting from field mapping and the measurement of stratigraphic sections in key-areas of the basinal domain, a geothematic field-work aimed at i) reconstructing the Tethyan Jurassic, rifting-related, depositional architecture characterised by a complex pattern of intrabasinal morpho-structural highs (pelagic carbonate platforms) and intervening deeper-water basins, ii) tracing the itineraries followed by sediment gravity flows shed by the margins of the neighbouring Lazio-Abruzzo Carbonate Platform and recorded in the pelagic succession, and iii) assessing the role played by the Jurassic submarine topography in funnelling and diverting the neritic material travelling across the basin, has been performed. In order to meet these goals, the identification in the field of exhumed palaeoescarpment tracts bordering pelagic carbonate platforms is mandatory, since field evidence indicates that the horst-block margins formed obstacles to the gravity flows as sediment load was discharged in confined basins at their toes. In some cases, depending on their orientation with respect to the main palaeo-flow axes, palaeoescarpments caused the partial or total deflection of turbidity flows, as highlighted by turbiditic deposits running parallel to them and the occurrence of sedimentary structures migrating upflow. While turbidity currents were locally vigorous enough to climb the escarpments, leaving overbank deposits on the pelagic carbonate platform-tops, a "shelter" effect is evidenced by the resediment-free nature of those basins lying downflow, which were shielded by the intrabasinal highs.

3D mapping in a 2D country: a new geological map of the Kingdom of the Netherlands

Jeroen Schokker, Marcel Bakker, Reinder Reindersma, Nikki Trabucho, Michiel van der Meulen & Sytze van Heteren

TNO, Geological Survey of the Netherlands; jeroen.schokker@tno.nl

On the occasion of its centenary anniversary, the Geological Survey of the Netherlands presented a new geological map of the Kingdom of the Netherlands. This first nationwide map since 1975 does not only include the onshore and offshore European Netherlands, but also the Caribbean part of the Kingdom. Besides near-surface deposits and rocks, important fault lines and maximum ice extent during previous glacial periods are depicted. Three cross sections illustrate the relation between the shallow and deep subsurface.

The map, on a scale of 1:600,000, summarises our present knowledge of the subsurface. It aims to illustrate the rich geological history of the Kingdom to professionals and the general public alike. From an applied perspective, it highlights the potential of geological resources and the presence of geohazards. For example, it shows where to find shallow marine sand and gravel resources necessary for offshore construction activities and coastal maintenance. Two of the Caribbean islands are dominated by active volcanoes, all of the islands run the risk of earthquakes and tsunamis, and tropical hurricanes frequently lead to coastal erosion, flooding and landslides on certain parts of the islands.

By applying a profile-type legend, describing unit sequences rather than just the top unit, we are able to show information from our 3D digital mapping on a 2D map. It gives maximum insight into the geological history of the country and clearly demonstrates the occurrence of similar deposits on both sides of the current coastline. One of our biggest challenges was to construct a harmonised legend respecting the diversity of the onshore and offshore geology, yet simple enough to be readily understandable.

The map forms the Dutch contribution to international projects like the International Quaternary Map of Europe (IQuaME 2500) and the European Marine Observation and Data network (EMODnet). It is also the starting point of renewed and intensified mapping of the Caribbean islands Aruba, Bonaire, Curaçao, Saba, Statia, and St. Martin. Finally, this paper map helps the Survey to market state-of-the-art digital subsurface models that are much more suitable for resource and risk analysis, but more difficult to understand.

Subsurface Mapping of the Cretaceous Carbonate Platform in Oman

Henk Droste

University of Oxford

Subsurface mapping using seismic data had a major impact on the understanding of stratigraphy. It is the only tool that allows to laterally follow chronostratigraphic surfaces over 10's to 100's of km and assess the nature of lateral stratigraphic changes. The new insights led to concepts such as sequence stratigraphy in the late 70's which are now widely used in both outcrop and subsurface studies. The arrival of 3-D seismic in the 1990's and the continuous improvement of seismic quality allowed for even more detailed studies of the stratigraphic architecture of both clastic and carbonate depositional systems in space and time. An example of new insights based on subsurface mapping is the improved understanding of the stratigraphic architecture of the Cretaceous carbonate platform in Oman. This was a laterally extensive epeiric platform, more than 1 km thick, that covered most of Oman and the Arabian Plate during Early to middle Cretaceous times. The previous models for these epeiric carbonates assume a layer-cake stratigraphy with very low depositional gradients, broad facies belts and gradual facies transitions. Studies using high-resolution 3-D seismic data show that these classical epeiric carbonates have a complex internal architecture, with abundant inclined stratal and mounded stratal geometries. The slope angles imaged on seismic have dips of 0.5 – 5˚, much steeper than suggested in studies based on only outcrop or well data. Mapping of these geometries show that the epeiric platform is built by a stacking of depositional sequences with a similar internal stratigraphic architecture. This starts with differential carbonate growth and the development of a topography of shallow carbonate shoals and intra-platform basins with water depths reaching several tens to 100 m. This is followed by a progressive infill with prograding carbonate shoal complexes and ending with subaerial exposure. Though much detail can be obtained from seismic, interpretation should always be checked for possible artifacts. These could be related to velocity changes caused by lateral changes in rock properties or differences in burial depth affecting resolution, but also to the exaggeration of the vertical scale that is often used when interpreting the seismic.

Session 10

KEYNOTE: From map and compass to 3D models and digital outcrops: how biases influence mapping and interpretation.

Clare E. Bond

University of Aberdeen

From map and compass to 3D models and digital outcrops: how biases influence mapping and interpretation

William Smith's map is an interpretation of the UK geology we would see it were not for soil, vegetation and building cover. The map also implies a 3D geometry of the rocks in the subsurface. A geological map, such as William Smith's, is an interpretation formed around scattered data points. The data provide constraint from which the map is built; and much of the certainty derives from the geological reasoning processes employed by the creator. For the viewer the colourful presentation of the map implies a depth of understanding and accuracy that is not necessarily constrained. The reasoning processes that underpin the creation of a geological map hold the key to providing the viewer with a truer sense of certainty. Nonetheless, it is also useful for the viewer to understand the context of creation, including societal influences, and the dominant scientific thoughts of the time. This is because interpretation is affected by biases that we are all susceptible to. Simply, our reasoning processes are flawed and understanding how these present in, and influence maps and models is important for their future use. I explore some of these issues drawing on experiments and observations that reveal biases in geological maps and models.

3D digital models: accuracy, precision, and applications. Examples from central Sicily (Italy)

Martina Forzese

Dep. of Biological, Geological and Environmental Sciences, University of Catania, Italy

Maniscalco Rosanna (Dep. of Biological, Geological and Environmental Sciences, University of Catania, Italy), Butler Robert WH (Dep. of Geology and Petroleum Geology, University of Aberdeen, UK)

Photogrammetric Structure from Motion (SfM) is a fast and low-cost methodology using aerial photography, generally from UAVs, to generate highly accurate (from metric to centimetric scale) 3D maps of geological outcrops and areas. The global Covid pandemic has driven increased demand for these products to create 3D digital outcrops to enhance education, tourism and enterprise. In this study, we share results from selected outcrops within the Riserva Naturale Orientata Monte Capodarso e Valle dell'Imera Meridionale of central Sicily (Caltanissetta and Enna districts). The reserve contains spectacular outcrops of Plio-Pleistocene coastal packstone units that chart the interaction between sea-level changes and fold amplification. Images were acquired using flights of a DJI quadri-copter drone, flying at an average height of 70 meters. This yields an overall resolution of 4-5cm/px, after processing with Agisoft Photoscan Professional. The total areal coverage is around 7 km2 with c. 480 meters of relief. To minimise distortion and for georeferencing, we collected a. 18 GCP (Ground Control Points) and a. 6 CP (Check points) after the drone acquisition process in the field. However, further studies on the accuracy, precision, and quality of data are required. For a preliminary check on model accuracy, we compare our point cloud with satellite, DTM (Digital Terrain Model) and other GIS surveys. The resultant 3D model will establish detailed tilt histories for fold-limbs and provide a framework for correlating eustatic sea-level variations within the outcrop area. On the other hand, although the Mt. Capodarso area lies in the UNESCO Global Geopark and preserve a valuable geo- and archaeological heritage, it is highly exposed to ongoing landslides and rockfalls, which make extremely hard the enhancement of the geotourism. Accurate landslides and rockfalls mapping on the orthomosaic, generated from the 3D model, allowed to identify and trace new and safer geotrekking trails to boost the experience of the natural park and its geo-archaeological resources. The 3D model will also provide a 360° view of the geosites and increase territory awareness.

Strategies for Subsurface Mapping: A Journey to Computational Efficiency and Enhanced Modelling

Gwynfor Alun Price Jones

Halliburton ,97 Milton Park, Abingdon OX14 4RW, UK

Owen Sutcliffe (Halliburton,97 Milton Park, Abingdon OX14 4RW, UK) Thomas Jewell (Halliburton,97 Milton Park, Abingdon OX14 4RW, UK) Rafael Garcia (Halliburton, 3000 North Sam Houston Parkway East, Houston TX 77032)

The distribution of lithologies and fluids (and all of their associated properties) in the subsurface is heterogeneous at a variety of scales and even in the most data-rich settings our models are imprecise. This lack of precision reflects the fact that:

- Subsurface models are mostly derived from data with distinct scales of resolution (core, petrophysical logs and seismic as examples)
- They are actually aggregated models or realizations that have their own unique set of assumptions or uncertainties for each component (e.g. velocities models and gross depositional environment maps) and;
- Environments that are or were available for the visualization of models and/or the processing of simulations restrict the ability to resolve mapping products.

In industry today, the construction of subsurface models to deliver a Digital Twin is required not only to provide insight into the distribution and scale of exploitable resources but also to generate a considered framework for prediction in the exploration for new resources. In any campaign, whether focused on exploration or development, the main cornerstone of it is the acquisition of new data in order to help reduce uncertainty and lower the risk on the investment. In today's industry, subsurface models are required to be rapidly updated, maintain data fidelity, are integrated across a range of scale, accurately depict complexities and have an appreciation for the uncertainties revealed by running multiple realization of the data-based model. In the past, such qualities were pre-emptive (or laborious to deliver) when models were integrated in flat 2D environments by hand. Early mapping and modelling tools were automations of manual techniques, major developments in computational technologies have now revolutionized both how we map, assess and model the subsurface. Elements of this evolution will be described as we are now truly in the 4th generation of subsurface mapping.

Supporting The Goal Of Net Zero Via Carbon Capture And Utilisation Storage With AI Derived Interpretation

Ryan Michael Williams

Geoteric

Peter Szafian (Geoteric)

Carbon Capture Utilisation and Storage (CCUS) is seen as a potential solution to the World's climate/carbon crisis. Around the world potential CCUS sites have been identified for CO2 storage, whether it be an abandoned hydrocarbon field or a subsurface aquifer. The Southern North Sea is thought to contain several highly prospective sites. Un-faulted, anticlinal mounds of Bunter Sandstone shaped by underlying salt pillowing are overlain by Triassic shales, forming a reliable trap and seal pairing. The presence of the Esmond gas field supports the ability of these formations to trap and store fluids within the subsurface. Using AI networks, it has been possible to investigate and interpret a Southern North Sea Bunter mound, for identification of a CCUS site location. Revealing the presence of faults within the site's location is of vital importance, not only for sealing potential and trap definition, but also to identify any aquifer compartmentalisation which may reduce the ability to successfully fill the structure. The AI fault detection network can also be fine-tuned to the specific style of faulting observed within the seismic volume. Extracting horizons from seismic data can be a time-consuming process, especially with complex faulting. Therefore, having the ability to extract every horizon within a volume can free up a significant portion of an interpreter's time, allowing them to concentrate in areas of complexity. Extracting all horizons will allow an interpreter to clearly visualise the structure and the lateral extents of aquifer/reservoir and seal pair with greater confidence. Combining the structural and stratigraphic analysis generated through AI means therefore allows for a quicker, more time efficient interpretation without any loss of accuracy. The ability to create quick, reliable, and consistent interpretation is key for successful CCUS site investigations. It is vital that the interpreter is involved throughout the AI interpretation process, as they have all the necessary experience, knowledge and skills. AI is subsequently allowing the interpreter to complete the work, save time and improve the quality of results.

The digital transformation of geological mapping and modelling

Tim Kearsey

British Geological Survey

Ford J R1, Bateson L1, Hughes L1, Kessler H1, Napier B1, Price S J2, Roper S1, Terrington L R1   1 British Geological Survey 2 Arup

Since the early days of geological mapping, geologists have used the latest tools and techniques to help deliver greater geological understanding: allowing deeper, more detailed and increasingly confident interpretations, overcoming physical challenges to reach ‘undiscovered’ geological terrains or dealing with the challenges of communicating with other disciplines. This talk focusses on the transformative role of digital tools and data in geological mapping and modelling. From the pioneering use of computing in geostatistics, digital cartography and remote sensing to 3D visualisation and the use of ruggedised PCs for fieldwork, digital systems present geologists with myriad benefits over traditional approaches. Fundamentally, this transformation is underpinned by the transition from analogue to digital data formats and the proliferation of open datasets and tools that allow their efficient and effective use by geologists. GIS and 3D modelling systems allow the creation of digital environments that integrate large and complex datasets for effective visualisation, interrogation and analysis. These digital environments maximise the value derived from data, generate increasingly contextual geological interpretations and enable the capture of 3D understanding that was hitherto restricted to static 2D or pseudo-3D representation. Intuitive 3D visualization software based on computer graphics technology allows geologists to recreate rich digital landscapes and carry out virtual field mapping in any part of the Earth and planets. By combining geological knowledge and interpretations with cultural data and spatial data from a wide range of sources it is possible to effectively communicate geological understanding and uncertainty to diverse user communities. Geologists have a track-record of successfully adopting and adapting technical advances to deliver robust geological maps and models. Increasing global coverage of high-bandwidth telecommunication, improved hardware and battery performance, more complete, open and connected datasets, and further breakthroughs in data workflows and analytics offer significant future benefits to geology both in the in the office and the field. However, it is vital that the growing use of complex and impressive digital tools and techniques for data assimilation, interpretation and visualisation continues to be coupled with ‘geological thinking’ based on, and contributing to, geologists’ increasing knowledge and experience.

Session Eleven

Geological Mapping in a Digital Age

Christopher Lambert

SRK Exploration Services

Geological mapping has been a fundamental tool in deciphering the complex geological history of our planet. Through carful observation, a skilled mapping geologist can apply their craft to a broad range of geoscientific problems. In mineral exploration, mapping is used to guide ongoing work and provides essential insights into the lithological and structural controls of mineralisation. Mapping has been used during early-stage exploration as a particularly cost-effective tool to facilitate the generation of targets and to assess prospectivity of an area. With the onset of the digital age, rapid innovations have characterised all industrial sectors and geology is no exception. The concepts of lithological and structural mapping have not changed over the years. However, the technologies and data available to geologists are constantly improving. Portable mapping devices has led to paperless mapping workflows that allow capture, integration and interpretation of data in the field. The commercialisation of drone technology now means that every geologist has potential access to high resolution imagery and 3-dimensional models. The advancements in geographical information systems (GIS) and remotely sensed data sets also provide the modern explorer and the wider geological community with a wealth of powerful tools at their fingertips. When integrated with the traditional mapping techniques, the result can be a highly efficient and effective workflow of targeted field work. This presentation will highlight the range of mapping tools and application available on the market in 2021. It will provide an example of a suggested modern mapping workflow, integrating traditional and digital mapping techniques to develop robust geological models and it will draw on an extensive list of mineral exploration case studies from a global setting.

The integration of virtual outcrop with traditional mapping, lessons for the future: examples from the Mull Lava Group, Isle of Mull, Scotland.

Jessica Pugsley

University of Aberdeen

Malcolm Hole, John Howell, David Jolley, Magda Chmielewska (University of Aberdeen)

Since March 2020, virtual outcrop (VO) has become an indispensable teaching tool during a time of restricted travel. The benefits of VO, however, extend far beyond that of a fieldwork replacement, as highlighted within this four-year study of volcanic stratigraphy on the Isle of Mull, NW Scotland. Despite being located within the intensely studied British Palaeogene Igneous Province, the volcanic stratigraphy of NW Mull has not been re-examined, other than geochemically, in almost a century since the initial mapping. Advancements in our understanding of volcanic processes, and field and lab-techniques for analysing volcanic stratigraphy, provide an opportunity to study such areas in a far more accurate and detailed way than was possible 100 years ago. The initial mapping of a century ago describes a relatively simple stratigraphy of lava, interbedded with paleosol ('bole'), crosscut by minor intrusions. Instead, our extensive fieldwork, supplemented by virtual outcrop, demonstrates a highly heterogeneous volcanic stratigraphy, including several unidentified intra-lava deposits such as volcaniclastic conglomerates and sandstones. This stratigraphy is also extensively faulted both syn- and post- emplacement of lava. The virtual outcrop facilitates a visual side-by-side comparison of stratigraphy within disparate fault-blocks, exposed kilometres apart. Identifying key marker horizons, enables correlations to be made across the fault-blocks and development of a stratigraphic framework. This case study from NW Mull demonstrates that by integrating new technology with traditional mapping, fresh insights can be gained even in one of the world's most prolifically studied volcanic provinces. The workflows established during this case study can be applied not only to other ancient volcanic provinces, but also future geological mapping studies within volcanic or sedimentary settings globally.

Geological mapping on Mars using 3D virtual outcrop analysis techniques

Robert Barnes

Imperial College London

Sanjeev Gupta (Imperial College London), Gerhard Paar (Joanneum Research), Thomas Ortner (VRVis), Matt Gunn (Aberystwyth University), Ariel Ladegaard (Aberystwyth University), Arnold Bauer (Joanneum Research), Christoph Traxler (VRVis), Piluca Caballo (Jo

Geological mapping on Mars drives scientific investigations by robotic exploration mission science teams engaging in the search for evidence of ancient extra-terrestrial life. On the ground, orbitally- derived mapping is combined with mapping conducted on panoramic images collected by stereo panoramic camera systems, such as the Mastcam and Mastcam-Z on NASA's rovers Curiosity and Perseverance and the PanCam on ESA/ROSCOSMOS's Exomars Rover Rosalind Franklin. Quantitative analysis of 2D panoramas is time consuming, imprecise, and lacking in spatial context. Inspired by virtual outcrop geology techniques utilised in terrestrial geology, we have developed a workflow for 3D geological analysis of stereo-images from Mars. Semi-global feature matching of stereo-images in the Planetary Robotics Vison Processing (PRoViP) tool incorporates camera pointing and positioning information to create scaled, textured digital terrain models – Ordered Point Clouds (OPCs). Resultant OPCs are rendered in the Planetary Robotics 3D viewer (PRo3D) for visualisation and analysis, allowing the user to interpret data collected from multiple locations in one 3D environment, as well as collect distance and dip and strike measurements directly from the OPCs. We apply this workflow to fluvial outcrops at Shaler visited during the Curiosity mission and Proterozoic terrestrial lacustrine deposits of the Diabaig Formation, Scotland, imaged with an emulator for the ExoMars PanCam instrument for terrestrial assessment and validation. Shaler is comprised of packages of composite cross-laminations with cumulative thicknesses of 1.7 – 2.8 m, superimposed on bed surfaces dipping 10°-25° to the southeast. The 35-45 cm thick packages of sandstone form wedge-shaped geometries in cross-section, comparable to those observed in terrestrial barforms. The basal units contain cross laminations formed by southerly palaeocurrents, and in the upper units show dominantly northeasterly palaeocurrents. The dominant formation process was lateral accretion on surfaces dipping 14° to 113° with dune migration towards the northeast. The lacustrine facies in the Diabaig are characterised by siltstones and mudstones with fine sub-mm to mm scale laminations, 0.5 – 2 cm thick symmetrical ripples with 2 – 5 cm spacing, and intercalated sandstone often reworked to form 1-10 mm thick lenses draped by sub-mm mudstone and siltstone laminations. Enigmatic syn-depositional, commonly elongate (trending ~140°-320°) antiformal features are common in the laminated siltstones, with widths from 20 cm to 50 cm and amplitudes of 5-10 cm. Variable water levels are evidenced by desiccation cracks in the lacustrine mudstones occurring at multiple stratigraphic intervals and infilled with coarse clastic material. We analysed image and DOM data of the Diabaig collected at variable distances from the outcrops to determine the fidelity of the data with respect to field observations and ground control measurements. Multiple DOM analyses along a rover traverse, with terrestrial validation, will greatly enhance the scientific return from robotic exploration missions.

Virtual Outcrops and Virtual Field Trips, Sharing and Disseminating Outcrop Information: Lesson from a Global Pandemic

John Howell

University of Aberdeen

Pugsley J., Chmielewska M., Maxwell G. , Hartley A., Schofield N., Brackenridge R. (University of Aberdeen) Buckley S., and Naumann N. (NORCE Research, Bergen)

Over the past 20 years, virtual outcrops have transitioned from a niche research area into a mainstream tool in the geoscientist's arsenal. The advent of inexpensive consumer UAVs (drones), easy to use processing software and dedicated interpretation software have resulted in an explosion in their uptake which was accelerated by the COVID pandemic. This increase in uptake has facilitated to issues, firstly how to share models within the community and secondly how to optimize their use in Virtual Fieldtrips. There have been several initiatives to facilitate the public sharing of virtual outcrop data via website and online databases. V3Geo.com was launched in April 2020 to provide virtual outcrop data to groups and institutions who were unable to visit the field due to the global lockdown. The site allows search and navigate around virtual outcrops from over 250 key geological sites. The most recent release allows anyone to up-load and publish their own models directly. There is a long term goal of providing a public resource that captures all of the key outcrops in the World and beyond. This presentation will also systematical review the use of Virtual Fieldtrips (VFTs) during the global pandemic. Data were collected from two separate multiday VFTs constructed and delivered to MSc. students at the University of Aberdeen. The VFTs were a direct replacement for traditional trips to Utah (USA) and the Pyrenees (Spain) and incorporated broadly similar localities and learning goals as physical trips in previous years. Virtual outcrops were presented in LIME and integrated various data including VOs, sedimentary logs, field photos, geological maps, figures, 360° photos, DEMs and gigapans. At the end of each course a questionnaire was issued to appraise the effectiveness of the course, specially addressing the effectiveness of the delivery, the user experience, and the learning outcomes. Analysis of the results suggested that students (97%) would prefer the go to the field. This is largely for the same reasons people enjoy going on holiday and include visiting new places. More significantly, the desired learning outcomes were achieved, in most cases better than on traditional trips. 65% of students stated they learnt concepts they would not have during a traditional fieldtrip. Key advantages of the approach were, the ability to visit outcrops in a logical (rather than logistical order), significant time saving on travel, the ability to change the scale of observation rapidly and the ability to bring in analogue data at scale. Students were also more engaged, less distracted and less tired than on traditional trips. The results are still being analysed to optimize the delivery method, but they suggest that VFTs, based on VOs have a significant contribution to make to learning in the geosciences, either as stand-alone event or as an addition to traditional trips.

Virtual fieldtrips with real time remote collaboration as a better way communicate and understand geological processes.

Claudia Ruiz-Graham

Imaged Reality

Stavros Vrachliotis (Imaged Reality)

Geologists have a natural gravitation towards fieldtrips to understand the 3-Dimentionality and lateral variations of earth processes from basin to pore scale. The reality is that many times natural processes hide their secrets in inaccessible and dangerous locations. Even in roadcuts, safety risks can prohibit a close-up investigation of an outcrop. On the other hand, even in the friendliest environments, geologists are called to understand the large-scale tectonostratigraphic complexity of a geological site only by looking at a small "window" at the base of an outcrop. Too many times in the past geologists have been asked to understand geological processes on an outcrop by reviewing 2D paper-based diagrams on pre-reads and verbal descriptions from instructors. There is no doubt that Geology is 3D and human eyes and brain also understands space in 3D. Virtual reality places geologists in an immersive 3D digital space where they are surrounded by data whilst they experience the field in ways that in real life they cannot. Either by investigating and combining data at real scale or being able to study a geological site in the palm of their hand, geologists dramatically increase their understanding of geological processes in 3D. Immersion increases cognition and knowledge retention, improving decision making. Virtual reality also improves knowledge capture, by creating the option of field trip repeatability. Flying off a cliff in VR at real scale to examine the entire stratigraphic column, or rotating a 3D outcrop model in order to restore the pre-collisional setting allows geologists to have a better visual understanding of the field before and after visiting an outcrop. This practice has the advantage of more detailed geological observations in real fieldtrips and a robust knowledge retention of the outcrop locations. In this talk we will take you to a virtual fieldtrip, to depositional systems with examples across the globe using Stratbox, the first virtual reality platform for Geoscience.

The Rock Garden: creating a field course on campus to improve the accessibility of geological skills training

Thomas Wong Hearing

Department of Geology, Ghent University

Stijn Dewaele (Department of Geology, Ghent University), Stijn Albers (Department of Geology, Ghent University), Julie De Weirdt (Department of Geology, Ghent University), Marc De Batist (Department of Geology, Ghent University)

Field work is integral to most geoscience degrees and is a requirement of Geological Society accreditation. Typically, field skills training is concentrated into infrequent whole-day or longer residential excursions. However, the infrequency of field courses over a degree programme – even more so during a global health emergency – means that students do not regularly practice field skills and can lose confidence in their abilities between field courses. Furthermore, residential field courses can form multiple barriers – physical, financial, cultural – to accessing geoscience degree programmes. Being able to provide field skills training locally, in a familiar environment, in university term-time, and in normal working hours may help in dismantling some of these barriers and building student confidence in their practical skills. The Rock Garden is a newly developed on-campus geological field skills training resource at Ghent University designed to mitigate these concerns. Many geological field skills, including map-reading and field data acquisition and recording, are effectively taught in geological mapping exercises. The Rock Garden is designed to be comparable to an inland geological mapping exercise in Belgium. We produced an outcrop plan from a hypothetical geological structure to fit the available on-campus space, sourced outcrop material from local building stone companies and quarries, and dug the rocks in on Campus Sterre, around the Geology Department. The Rock Garden has already been used in partial mitigation of the impacts of coronavirus travel restrictions on undergraduate field teaching. Student mapping work was of comparable quality to that from ‘real-world’ field courses. Moreover, student enthusiasm for the Rock Garden was extremely high, and the students engaged in both the spirit and letter of the exercises. We do not consider the Rock Garden to be a substitute for ‘natural’ field courses, but do consider it a valuable asset to learning and maintaining geological field skills. The Rock Garden provides an introduction to geological field work in a familiar environment where accessibility barriers can be minimised. A campus-based resource like the Rock Garden provides one method for addressing accessibility and student confidence concerns in field skills training.

Session Twelve

Geological maps along the transect from the Lake Zone to the South Gobi Zone in SW Mongolia

Pavel Hanžl

Czech Geological Survey

Pavel Hanžl (Czech Geological Survey); Alexandra Guy (Czech Geological Survey); Battushig Altanbaatar (Mineral Resources and Petroleum Authority of Mongolia); Ondrej Lexa (Institute of Petrology and Structural Geology, Charles University Prague); Zuzana

The geological maps at a scale 1:500,000 covering central part of the Mongolian Altaids in southern Central Asian Orogenic Belt (CAOB) were compiled during the geological survey and scientific projects of the Czech Geological Survey in cooperation with Mineral Resources and Petroleum Authority of Mongolia and Institute of Geology, Mongolian Academy of Science in last two decades. The presented maps show complex relationships between lithotectonic units represented by ophiolites, volcanic arcs, different crustal levels of the various accretionary wedges and post-tectonic intrusions. The region of SW Mongolia has a basin and range topography with Neoproterozoic and Palaeozoic units exposed at NW–SE trending mountain ranges rising along major intracontinental faults and with intermontane basins filled by Mesozoic and Cenozoic sediments in between. The maps display clear N–S tectonic zonation featuring the Precambrian Baidrag microcontinent and the lower Palaeozoic Lake Zone in the north, the Palaeozoic sequences of the Gobi Altai and Trans Altai zones in the centre and the southerly South Gobi Zone. These geological units are exposed generally in NW–SE to E–W trending belts and were amalgamated during a long term accretionary proccesses from Neoproterozoic to Permian. NW–SE trends of gravity anomalies correlate well with the contact between the Trans Altai and the Gobi Altai zones, they are slightly reworked by E–W trending Gobi Tien Shan fault on the contact of the Trans Altai and South Gobi zones but the important first-order geological boundary between the Lake and Gobi Altai zones cannot be delineated by the gravity gradients. The published maps demonstrate the efficiency of using satellite imagery and geophysical data together with the field, geochronological and geochemical data assembled in GIS to provide a unique basis for all future geodynamic models and to define the architecture of the crust in remote regions with a high ore-deposit potential like in the Mongolian CAOB tract.

The structural and metamorphic evolution of the Zanskar Himalaya, Suru Valley, NW India

Ian Cawood

University of Oxford

Searle, M.1, Weller, O.2, St-Onge M.3 (1 University of Oxford, 2 University of Cambridge, 3 Geological Survey of Canada)

New geological mapping at (1:50,000) of the Zanskar Himalaya together with detailed macro- and micro-structural observations are used to constrain models of how the metamorphic rocks of the Greater Himalayan Sequence (GHS) deformed during continental collision. In this study, we focus on the Suru Valley of the western Himalaya, where the GHS is bound to the northeast by the Zanskar Shear Zone (ZSZ), and to the southwest by the Main Central Thrust (MCT) zone. In particular, we document the relationships between folds, thrusts, deformation fabrics and metamorphic isograds, to determine the sequence of deformation events and the spatial and temporal evolution of thickened Himalayan crust. Field and petrographic observations document three sets of penetrative planar and/or linear structural elements that are folded by late open regional folds. Peak metamorphic porphyroblasts are observed to grow syn- to post-tectonically, consistent with map-scale observations of Barrovian mineral isograds (biotite-in to sillimanite-K-feldspar-in) being subparallel, to locally discordant, with major penetrative structures. These observations indicate that the thermal peak occurred after the cessation of southwest-verging penetrative deformation in the study region. Top-to-northeast, normal shear sense fabrics associated with the ZSZ locally overprint the GHS compressional fabrics. In the eastern part of the study area, the shear zone juxtaposes low-grade metasedimentary rocks of the Tethyan Himalayan Series (THS) in the hanging wall with GHS units in the footwall; a relationship observed throughout much of the Himalaya. However, in the western part of the study area, the ZSZ is bound by undeformed and deformed Dras Volcanics (upper Jurassic-Cretaceous age volcanics thrust over the Indian passive margin[1]) in the hanging wall and footwall suggestive of limited throw across the shear zone in the west. This study illustrates how detailed field maps, records of fabric and mineral development, and structural cross sections may be used to constrain crustal thickening, metamorphism and exhumation in a collisional mountain belt. Some of the results indicate that the GHS may have a more heterogeneous along-strike structural and metamorphic evolution than previously documented.

Mapping Mount Everest

Mike Searle

University of Oxford

Since the discovery of the highest mountain on Earth during the mapping of India by the Great Trigonometrical Survey (1823-1852) and subsequent geographical, topographic and photogrammetrical surveys, notably by Moorshead (1921), Spender (1935) and Washburn (1988), geological mapping began with the maps and observations of Noel Odell (1924) and Lawrence Wager (1933). The first complete geological map of the Mount Everest – Makalu region (Searle, 2003) resulted from six expeditions to the Nepal (Sola Khumbu, Barun glaciers) and Tibet Rongbuk, Kangshung glaciers) sides of the mountain (1997-2003). Perhaps the most surprising discovery was that the highest mountain on Earth was cut by two large-scale, north-dipping, low-angle normal faults, the upper Qomolangma detachment separating the summit Cambrian-Ordovician fossiliferous limestones above from regionally metamorphosed mainly pelitic rocks (Everest Series) below. The older, lower normal fault, the Nuptse detachment, varies from an almost continuous section to a gradational ductile shear zone through the upper part of the Greater Himalayan Sequence. Downward increasing metamorphic grade and Pressure-Temperatures conditions are recorded in a continuous series of meta-pelites in biotite, garnet, staurolite, kyanite, sillimanite + muscovite gneisses, and sillimanite + K-feldspar migmatites, coeval with intrusion of a thick sequence of Miocene leucogranite sills (muscovite, garnet, tourmaline, ± sillimanite, cordierite, andalusite leucogranites). The downward decrease in metamorphic grade beneath the South Tibetan Detachment (STD) system is concomitant with the inverted metamorphic field and PT gradient across the Main Central Thrust (MCT) zone, structurally along the base of the GHS. Together these facts show that the GHS was extruded to the south by up to ca 120 km, bounded by the STD low-angle normal fault above and the MCT south-vergent thrust below, during the late Oligocene – Miocene (Channel flow model)

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