Digitising Svalbard's geology: the Festningen digital outcrop model

Kim Senger[1*], Peter Betlem[1,2], Tom Birchall[1], Luiz Gonzaga Jr[3], Sten-Andreas Grundvåg[1,4], Rafael Kenji Horota[1,5], Andreas Laake[6], Lilith Kuckero[7], Atle Mørk[8], Sverre Planke[9,2], Nil Rodes[1] and Aleksandra Smyrak-Sikora[1].

Abstract

The renowned Festningen section in the outer part of Isfjorden, western Spitsbergen, offers a c. 7 km-long nearly continuous stratigraphic section of Lower Carboniferous to Cenozoic strata, spanning nearly 300 million years of geological history. Tectonic deformation associated with the Paleogene West-Spitsbergen-Fold-and-Thrust belt tilted the strata to near-vertical, allowing easy access to the section along the shoreline. The Festningen section is a regionally important stratigraphic reference profile, and thus a key locality for any geologist visiting Svalbard. The lithology variations, dinosaur footprints, and the many fossil groups, record more than 300 million years of continental drift, climate change, and sea level variations. In addition, the Festningen section is the only natural geoscientific monument protected by law (i.e. geotope) in Svalbard. In this contribution, we present a digital outcrop model (DOM) of the Festningen section processed from 3762 drone photographs. The resulting high-resolution model offers detail down to 7.01 mm, covers an area of 0.8 km^2 and can be freely accessed via the Svalbox database. Through Svalbox, we also put the Festningen model in a regional geological context by comparing it to nearby offshore seismic, exploration boreholes penetrating the same stratigraphy and publications on the deep-time paleoclimate trends recorded at Festningen.

Introduction

Explorationists traditionally are excellent integrators – utilizing geological concept models together with seismic, borehole and other sub-surface data to find and exploit hydrocarbons or store CO_2. Outcrops are crucial in this context, as they truly bridge the resolution gap from seismic to well data (Figure 1). Outcrops can be used to characterize reservoir and cap rock heterogeneity, provide quantitative information on internal seals or baffles and illustrate the wide range of faults and fractures 'invisible' in the subsurface data. It is thus unsurprising that outcrops have been used by the petroleum industry for decades (Howell et al. 2014), with the Arctic archipelago of Svalbard a well-known and well-studied analogue for both the Barents Shelf and other Arctic Basins (Henriksen et al. 2011).

The last decade, however, was marked by a revolution comparable to the advent of 3D seismic for the subsurface (Marques Jr et al. 2020) – the exponential generation of digital outcrop models using affordable consumer-grade hardware (especially drones, and in recent years also smartphone-integrated light detection and ranging, i.e. lidar, scanners; Luetzenburg et al. 2021). Coupled with user-friendly structure-from-motion software it is now possible to generate georeferenced digital outcrop models from hand samples to 'seismic-scale' outcrops at a fraction of the cost of terrestrial or helicopter-based lidar scanning that was routinely used previously (Buckley et al. 2008).

Digital outcrop models irrespective of acquisition methods provide a high-resolution geo-referenced representation of the outcrops (Marques Jr et al. 2020). They are widely accessible to geoscientists and provide access to the outcrops at a fraction of the environmental and economic cost of traditional fieldwork, especially in remote areas like Svalbard. Furthermore, DOMs provide safe access to otherwise inaccessible steep cliffs or hazardous areas. Digitization of outcrops is also important for their preservation, for instance due to infrastructure construction covering the outcrop or coastal or other erosion. Finally, digital outcrops can be spatially integrated with other complementary data sets, for instance ground-penetrating radar or electrical resistivity tomography.

The acquisition and processing of digital outcrop models by both lidar scanners and using structure-from-motion is well covered in the literature. Similarly, many uses of extraction of quantitative data from digital outcrops are available, including deciphering the sedimentological and structural evolution of an area. As such, digital outcrops represent ideal input data for

[1] The University Centre in Svalbard | [2] University of Oslo | [3] University of Vale do Rio dos Sinos
[4] University of Tromsø - the Arctic University of Norway | [5] University of Bergen
[6] Schlumberger GmbH Aachen Technology Center | [7] Kuckero Science Services | [8] Independent Researcher | [9] VBPR AS
[*] Corresponding author, E-mail: kim.senger@unis.no

DOI: 10.3997/1365-2397.fb2022021

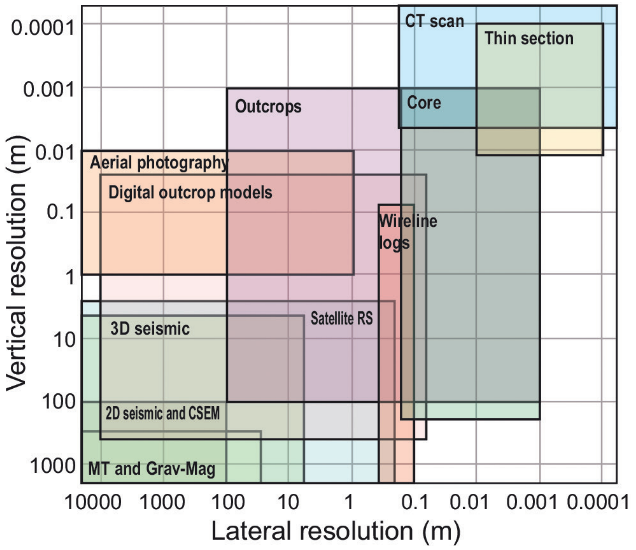

Figure 1 Vertical and lateral resolution of a range of geoscientific data sets, illustrating the importance of outcrops as a bridge between large-scale regional 'basin-scale' data sets, borehole data and detailed analyses on sample or drill core scale. The integration of data across scales and data types is critical to understand the big picture. Figure updated from Senger et al. (2021a), inspired by Matt Hall (Agile Geoscience) and Rarity et al. (2014). MT = Magnetotelluric, CSEM = Controlled-source electromagnetic, RS = remote sensing, CT = computed tomography.

making outcrop-based geomodels (Larssen et al. 2020). These can be used for instance in flow simulations (Cabello et al. 2018), or to generate synthetic seismic images of the outcrops (Lubrano-Lavadera et al. 2019).

In Svalbard, the systematic digitization of outcrops is one of the key goals of the Svalbox database (Senger et al. 2021a). In addition to acquiring and sharing digital outcrop models, the Svalbox platform allows them to be seamlessly integrated with other geoscientific data sets in an online map interface (www.svalbox.no) and in integration projects within Petrel. Svalbard, a Norwegian high Arctic Archipelago, is a true geologists' paradise – with exceptional outcrops illustrating both extensional and compressional tectonics, and a wide range of lithologies present in the rock record. The Devonian to Paleogene stratigraphic record is nearly complete, and records both the northward drift of Svalbard and a changing global climate. Svalbard's communities have been founded near local coal resources, exploited for the past century. What is less known, however, is that Norway's oil adventure did in fact start onshore Svalbard, where 18 wildcat boreholes were drilled from 1961 to 1994 (Senger et al. 2019). Coupled with the exceptional vegetation-free outcrops that Svalbard has to offer, these boreholes, related seismic data (Eiken 1985) and previous geoscientific research in Svalbard provide an exceptional foundation for the Svalbox database (Senger et al. 2021b). The Festningen Geotope, Svalbard's only protected area because of its geological heritage, is an exceptional outcrop displaying Carboniferous through to Cretaceous and Paleogene strata well exposed along a ca. 7 km-long beach section (Mørk and Grundvåg 2020).

To fully utilize digital outcrops within the petroleum industry's transition, relevant DOMs must be available to the community, ideally using FAIR principles (i.e. findable, accessible, interoperable and reusable; Wilkinson et al. 2016). As with any outcrops, they should be seen in the context of the regional geology – integration with all other available geoscientific data is thus imperative. While there are many global and local online databases of digital outcrops, notably V3Geo (Buckley et al. 2021), most do not allow users to download the models themselves for further usage.

In this contribution, we showcase the ongoing digitization of Svalbard through the Svalbox database. Specifically, we present a digital outcrop model of the Festningen Geotope section and illustrate how the model can be seamlessly integrated with other geoscientific data such as exploration boreholes, seismic profiles, publications and remote sensing data. Finally, we discuss the broader implications of the Festningen digital model within the Svalbard-wide Svalbox database.

The Festningen profile — a geological track record

The renowned Festningen profile is located at the mouth of Isfjorden in western Spitsbergen (Figure 2) and offers excellent exposures of Lower Carboniferous to Paleogene sedimentary rocks. The profile is part of the Festningen Geotope Protected Area, a 16.6 km^2 large area (14 km^2 onshore and 3 km^2 offshore) established on 26 September 2003 to protect its unique geological heritage. The first detailed geological cross-section and lithological descriptions of the Festningen profile were published by Hoel and Orvin (1937), while a revised open-access field guide was compiled by Mørk and Grundvåg (2020).

The strata exposed in the Festningen section is near vertically tilted due to its location at the eastern limb of the West Spitsber-

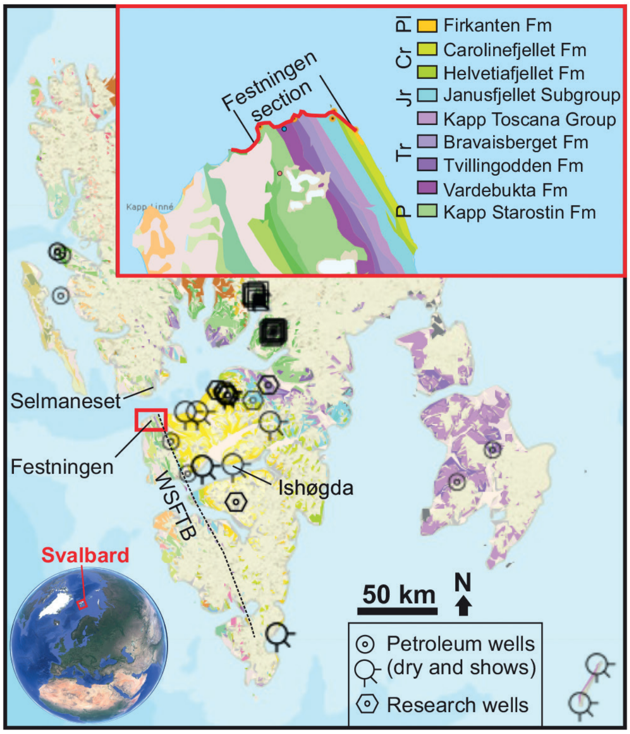

Figure 2 Geological map of Svalbard with the location of Festningen and the extent of the digital outcrop model (red line). The West Spitsbergen Fold-and-Thrust belt (WSFTB) severely deformed the strata at Festningen. An interactive version of the map including a full legend is available at www.svalbox.no/map.

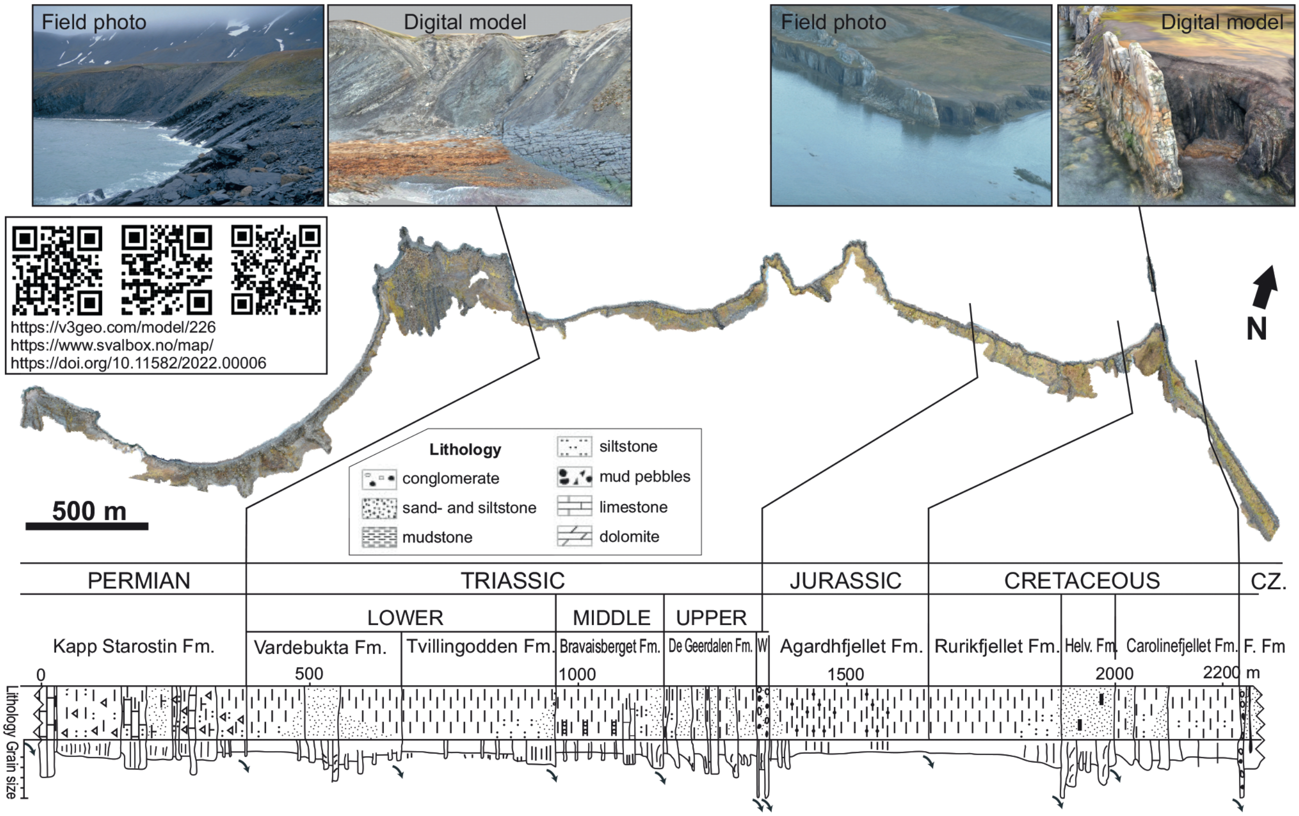

Figure 3 Stratigraphic column of the best preserved part of the Festningen section, from Mørk and Grundvåg (2020), tied to the digital model of the entire Festningen section. CZ = Cenozoic, W = Wilhelmøya Subgroup, Helv. Fm = Helvetiafjellet Fm, F. Fm = Firkanten Fm. The QR codes provide direct access to the digital model.

gen Fold-and-Thrust Belt, which formed when Greenland and Svalbard collided and passed each other during the Paleogene opening of the North Atlantic. The vertical nature of the strata offers easy access along the shoreline and makes it possible to walk through the entire section and thus experience 300 million years of geological history in a few hours (Mørk and Grundvåg 2020), walking up through the stratigraphy from west to east. Scattered outcrops of Lower Carboniferous conglomerates to Lower Permian anhydrite-bearing dolomites are present in the westernmost part of the section (Mørk and Grundvåg 2020). The classical part of the section starts with a thick brachiopod-limestone unit followed by spiculitic shales and bryozoan carbonates of the Upper Permian Kapp Starostin Formation (Figure 3). The Permian-Triassic (P-T) boundary marks a prominent shift from carbonates to siliciclastic sediments that dominate the entire Triassic-Cretaceous succession. As a result of the end-Permian mass extinction, the shales above the P-T boundary are devoid of burrows and other fossils (Grasby et al. 2015, Grasby et al. 2020, Schobben et al. 2020). The Triassic-Cretaceous succession is characterized by intercalated shales of marine origin and sandstone units of fluvio-deltaic to shallow marine origin (Grundvåg et al. 2019, Mørk et al. 1982, Nagy and Berge 2008; Figure 3). Several of these are time-equivalent units to important source rocks and reservoirs in the subsurface of the Barents Shelf (e.g., Henriksen et al. 2011). The characteristic Festningen Member sandstone at the base of the Lower Cretaceous Helvetiafjellet Formation, which resemble the walls of a medieval fortress, have given name to the entire section (Festningen translates to 'the fortress'). Dinosaur footprints, plant fossils and coals are present in the Helvetiafjellet Formation, reminding us that dinosaurs and temperate forests once thrived at these sub-polar latitudes (ca. 65°N paleolatitude; Dallmann 2015, Hurum et al. 2006, Vickers et al. 2016; Figure 3). A prominent quartz conglomerate at the base of the Paleocene Firkanten Formation, marks both the Mesozoic to Cenozoic boundary and a major hiatus where the entire Upper Cretaceous is missing (corresponding to a c. 47 million years time gap). This conglomerate, known as the Grønfjorden Bed, ends the classical Festningen section (Figure 3).

Acquisition and processing

The photographs used to generate the Festningen digital outcrop model were acquired on 15-16 September 2020 using an unmanned aerial vehicle (UAV; Mavic 2 Pro, 20MP Hasselblad camera). Data acquisition commenced in tripod mode (i.e., maximum speed of 1 metre/second). Photographs were taken automatically at set time intervals (e.g., 1 photo every 5 seconds ≈ metres; Figure 4a). Structure-from-motion photogrammetric (e.g., Westoby et al. 2012) processing using Agisoft Metashape (formerly PhotoScan, v1.7.2.12040) was conducted following the method of Over et al. (2021). Two consecutive photo alignment steps (full-image scale) resulted in the alignment of 3762 photos, leaving six unaligned (Figure 4b). Sparse cloud data (Figure 4c) were filtered on reconstruction uncertainty (level = 10), projection accuracy (level = 3), and reprojection error (level = 0.3) while skipping further tightening of the tie point accuracy (i.e., excluding Step 15). The dense cloud (Figure 4d; half-image scale, 'mild' filtering, 1 711 752 687 points) was confidence-based trimmed (removing level <= 1) and used as input for mesh (Figure 4e; including textures; 30 285

588 faces) and tiled model generation (Figure 4f). The filtering introduced a few low-point-density areas, mostly affecting debris slopes that were interpolated as part of the meshing process. The most affected section is a debris-covered area ca. 75 metres wide that lies ca. 150 m east of the P-T boundary. Georeferencing of the 7 km-long, 0.8 km^2 digital outcrop model (Figure 4; estimated total camera error: 3.57 m, ground resolution: 7.01 mm/pixel) relied on the drone-mounted GPS.

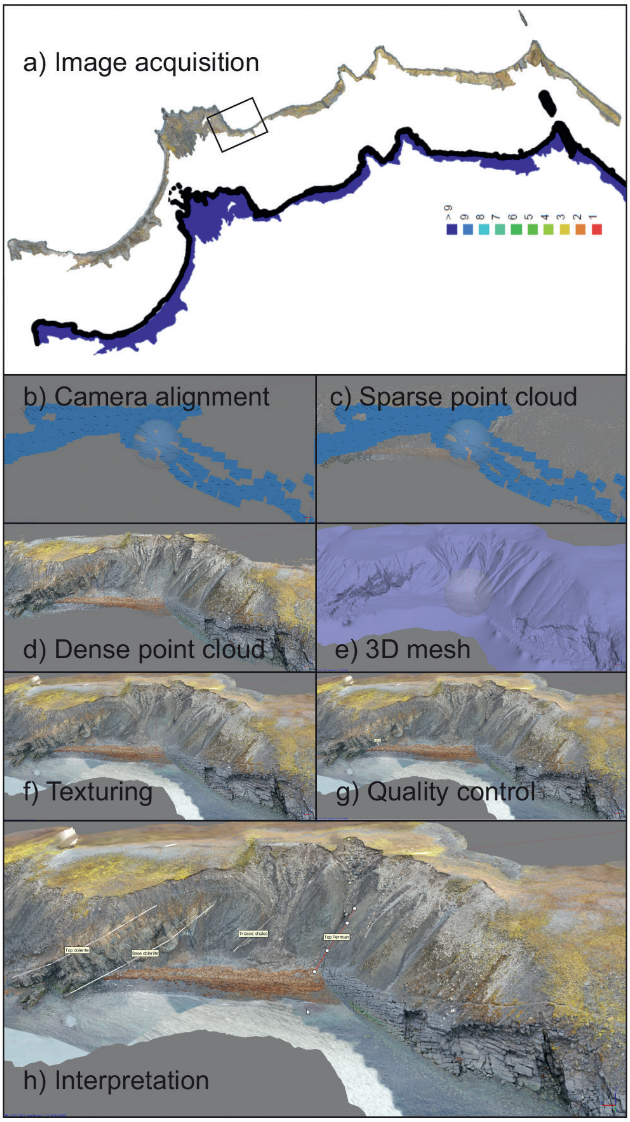

Figure 4 Acquisition and processing workflow. A) Spatial coverage of the 3757 photographs (black dots) used as input into the structure-from-motion processing steps. The subsequent panels illustrate the processing and interpretation steps (Figure 4B-H), zooming in on the Permian-Triassic boundary as located by the black rectangle.

Visualisation, sharing and storytelling

The full Festningen model (Figure 3), including input photographs, processing report, textured and tiled models, can be freely downloaded from an online repository (Betlem 2021). Visualisation and interpretation is possible in both freeware (for instance Agisoft's viewer, Blender) and subscription software like LIME (Buckley et al. 2019). The model is also viewable online through both Svalbox and V3Geo (Table 1).

The input photographs taken from ca. 28 m distance already provide high detail of a small part of the section (Figure 5). The processed models, however, allow semi-quantitative interpretation along the entire section. Details down to 5 cm are discernible on the model (Figure 5).

As part of the efforts to build geological stories around the acquired digital outcrop models in Svalbox, we have also generated several fieldtrips to the Festningen locality. These include a thematic fieldtrip on the evolution of fauna and flora within the succession (using the StoryMaps platform), and a general geological excursion guide building on 360° imagery (using the RoundMe platform; Table 1).

Integration and contextualization

The Festningen DOM is useful on its own, ideally coupled with the recently published field guide (Mørk and Grundvåg 2020). However, it is most powerful when integrated directly with other data sets in the area, including studies on the deep-time paleoclimate, seismic profiles, exploration boreholes or remote sensing data.

Festningen DOM as a calibration point for deep-time paleoclimate studies

The Festningen section has received considerable attention for deep-time paleoclimate studies as it represents the drift of Svalbard bedrock from the subtropical to polar latitudes and global climate change. The most studied events in the section include

Data set	Comments	URL/DOI/Reference
Digital model, input photographs and processing report	Available for download, also includes processing parameters and various versions of the model (Textured mesh in .obj, Agisoft tiled model etc.)	Betlem and Senger (2022)
Digital model	In context with other Svalbard geoscientific data. Can also be visualized in virtual reality	http://www.svalbox.no/portfolio/dom_2020-0001-festningen/
Digital model	Web-based platform with interpretation possibilities (V3Geo)	https://v3geo.com/model/226
Digital model	Web-based platform with virtual reality (SketchFab)	https://sketchfab.com/3d-models/svalbox-dom-2020-001-festningen-ef7a2031a4ee45da95019638a8ee6f90
Festningen – a digital lab on Svalbox	The Festningen Geotope – a laboratory for virtual field trips (VFTs). Includes links to VFTs on StoryMaps, Roundme, conference presentations and a fly-over video over the Festningen model	http://www.svalbox.no/the-festningen-geotope-a-laboratory-for-virtual-field-trips/
Geological field guide to Festningen	Includes descriptions and detailed field photographs	Mørk and Grundvåg (2020)

Table 1 Summary of all Festningen-related datasets available freely to the geoscience community.

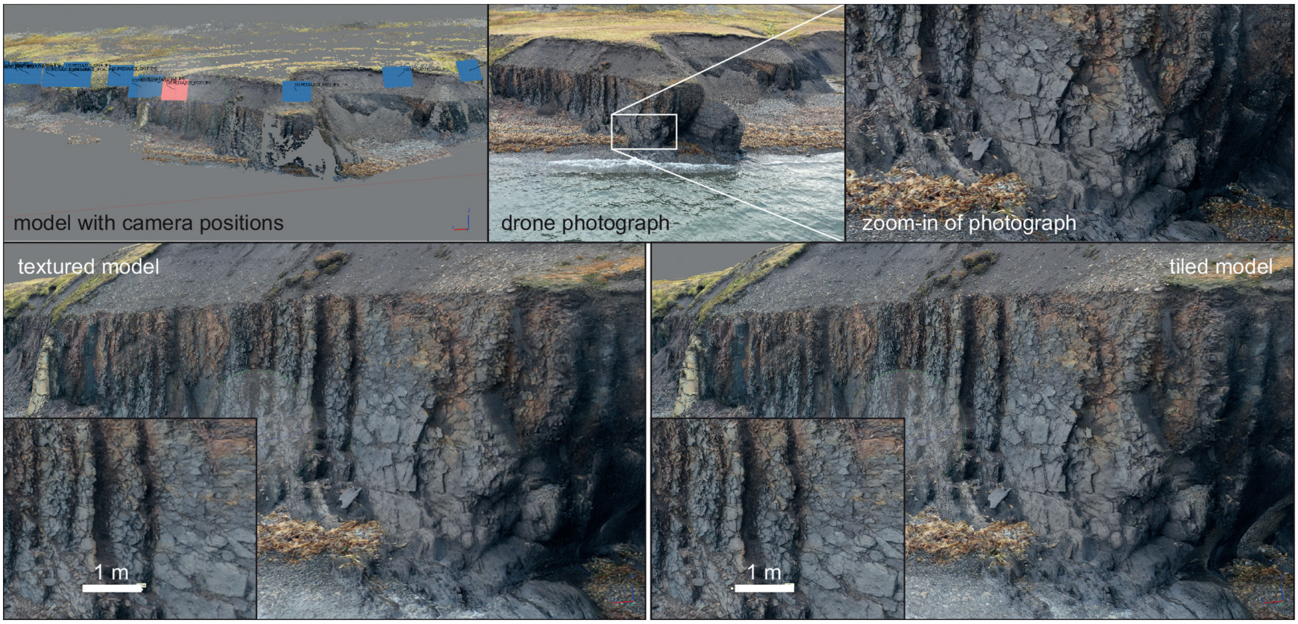

Figure 5 Comparison of level of detail discernible from a single drone photograph and the processed model (textured and tiled model types). Textured models render the entire model at the same time, while tiled models allow progressive rendering as the user zooms in, optimizing the computer's memory usage.

the end-Permian mass extinction (Grasby et al. 2015, Grasby et al. 2020, Schobben et al. 2020) and the Early Cretaceous climate fluctuations. The latter include the Aptian oceanic anoxic event 1a (OAE1a; Vickers et al. 2016) and cooling spikes in the overall greenhouse Cretaceous climate (Vickers et al. 2019). Furthermore, a well-known fossil of dinosaur footprints, which succumbed to coastal erosion some years ago, was presented by Hurum et al. (2006). These studies, along with the countless sedimentological, stratigraphic and structural studies published on Festningen, can use the digital Festningen model as a calibration point to link the various results (Figure 3).

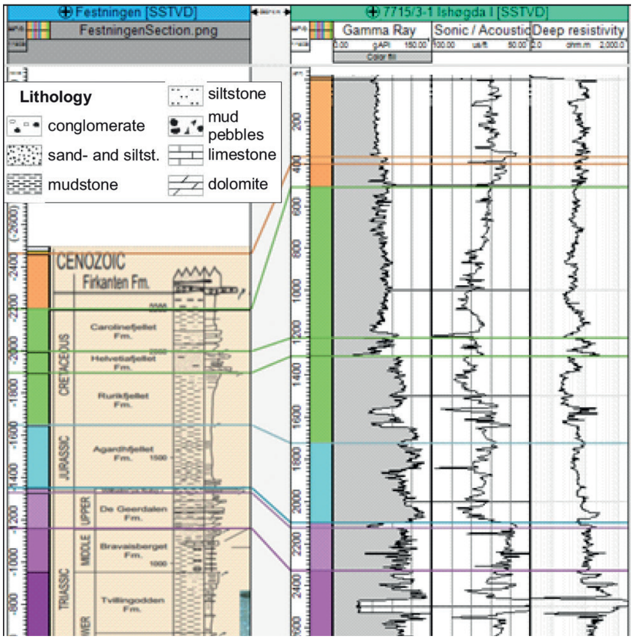

Figure 6 Correlation of the Festningen profile with Svalbard's deepest borehole at Ishøgda, flattened on the top of the Permian. Standard wireline logs presented are Gamma Ray, Sonic and Resistivity. Low grain size in the Festningen outcrop coarsely corresponds to higher Gamma Ray values in the borehole.

Exploration boreholes

The Festningen section can be directly correlated to Svalbard's deepest borehole, Ishøgda (3304 m to TD), located 55 km to the south-east and drilled in 1965-1966 (Figure 6; Senger et al. 2019). The borehole complements the outcrop data with wireline logs indicative of the overall rock properties of the penetrated strata (Figure 6).

Seismic and bathymetric data

Numerous seismic lines were acquired offshore from the Festningen section as part of petroleum exploration (Figure 7). While the quality is hampered by the structural complexity and high sediment velocity, the seismic data facilitate placing the section in the overall context of the West Spitsbergen Fold-and-Thrust Belt (Figure 7A). Published geological cross-sections (Figure 7B), based primarily on surface mapping, complement the regional understanding.

Remote sensing

The integration of the Festningen DOM with Svalbox regional geologic data such as DEM, satellite imagery, orthophotos and geological data provides the regional geological framework for the Festningen outcrop. Satellite imagery is ideally suited for lithological mapping in remote areas devoid of vegetation cover like Svalbard. The digital elevation model at 20 m resolution offers sufficient detail to map regional structural features, that can be correlated with geological maps through co-rendering in 3D (Figure 8).

Towards full immersion — Festningen in virtual reality

The Festningen section is also available through the Mosis Suite, a complete software system for outcrop sharing and interpretation (Vizlab 2022). Mosis Suite enables the visualization of point clouds, meshes, and textured models and the geometrical interpretation and measurement of DOMs using both traditional desktop setup and virtual reality (VR) headsets. The full Festningen DOM can be downloaded, visualized, and interpreted directly on Mosis XP/iXP (Desktop/VR). Supplementary high-resolution DOMs, digital sample models, 360° imagery, publications and laboratory analyses can be integrated within the same virtual augmented environment in Mosis Lab. This virtual environment provides the DOM visualization. At the same time, it enriches the virtual fieldwork with laboratory and computational results, mainly from the data, image and model correlation performed by machine learning and deep learning techniques.

Beyond Festningen — the Svalbox database

The Festningen profile is just one of an exponentially growing number of digital outcrop models available through the Svalbox database (Senger et al. 2021a, Senger et al. 2021b). It may be the most famous model since Festningen is Svalbard's only geotope, but it is far from the only one. The Selmaneset model (Figure 2), for instance, offers the same stratigraphy but on the northern shore of Isfjorden. Svalbox integrates not just the digital models, but places these in the regional geological context by accessing a wide range of geospatial layers (Figure 9). This spatial connectiveness of varied data sets spanning from the basin to the hand sample scale truly allows placing the digital outcrop models into an overall geological context.

Conclusions

In this contribution, we have presented a digital outcrop model of Svalbard's only geotope – the Festningen section. The model and all input data are freely available to the geoscience community, and the model can be visualized through several platforms, including in virtual reality. Furthermore, we have illustrated how the digital outcrop model can be seamlessly integrated with other geoscientific data sets, such as exploration boreholes and seismic data, through the Svalbox database. This exponentially growing database of in-context digital outcrop models is forming

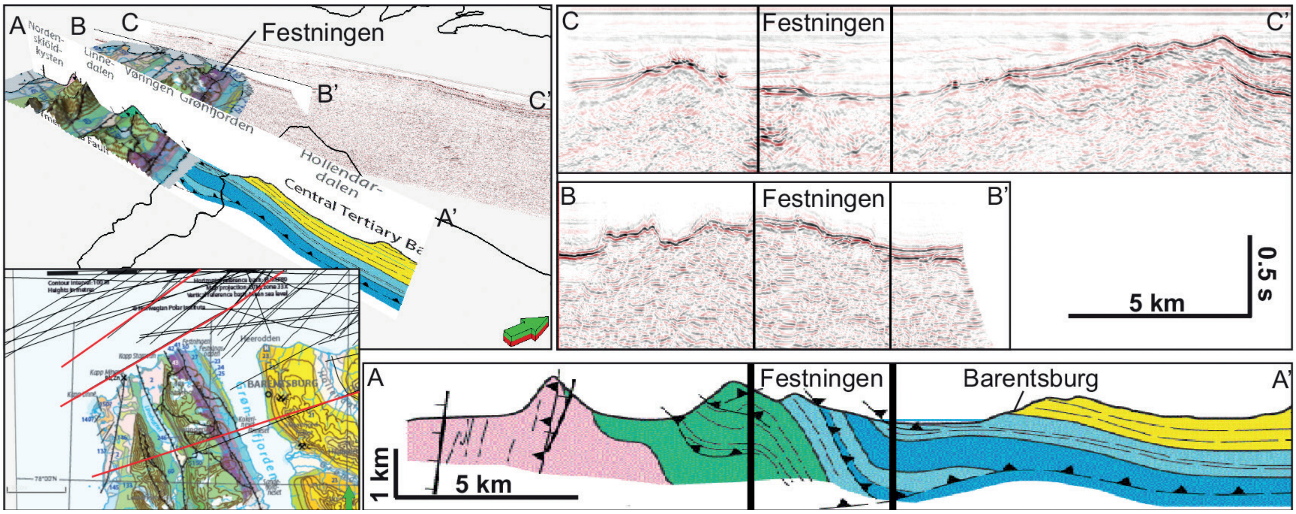

Figure 7 Putting the Festningen profile into a regional context by integration of published regional profiles (from Dallmann 2015) and two 2D seismic lines.

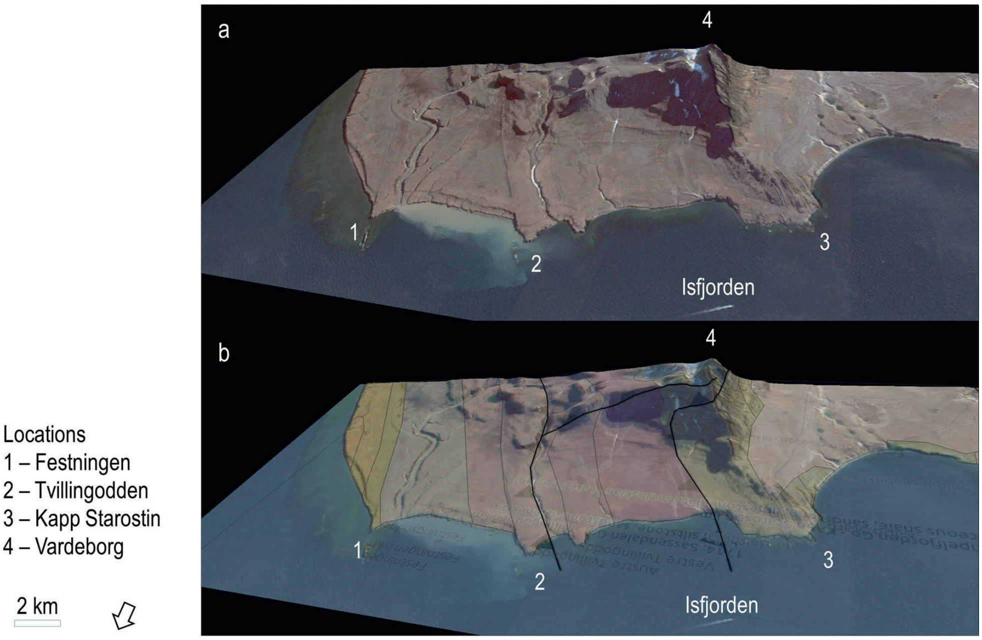

Figure 8 Remote sensing of the Festningen section. A) Satellite image draped over a 20 m regional digital elevation model (DEM). B) Co-rendering of satellite imagery and geological map.

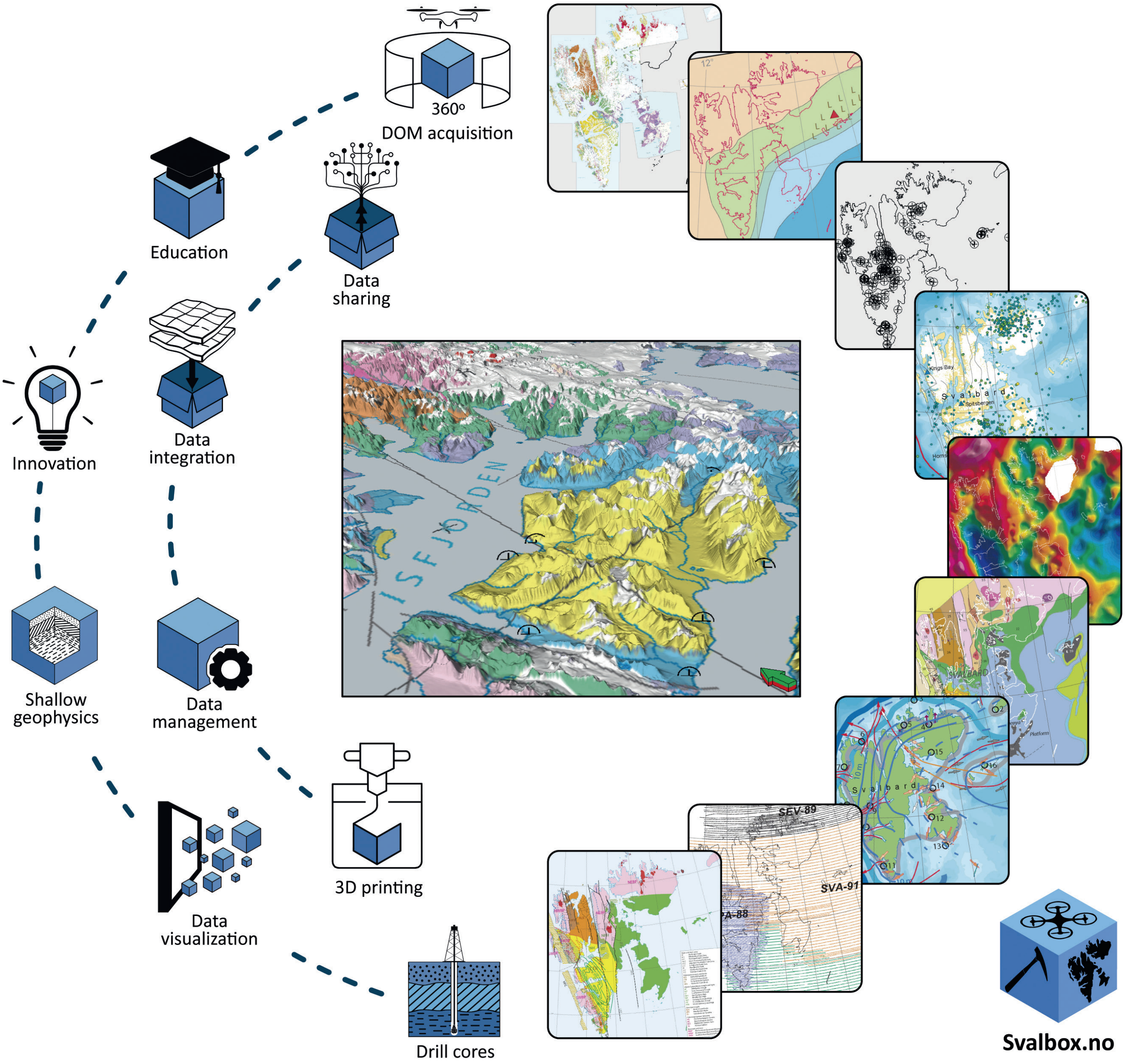

Figure 9 Key elements of the Svalbox concept, illustrating both the integration of different data sets and the innovative aspects of Svalbox. These include data acquisition (digital models, shallow geophysics, outcrop studies), data harvesting (from wells, geophysical data, remote sensing, publications etc.), data management (in a geospatial database in ArcGIS and Petrel), data integration (from basin to thin section scale, and across geoscientific disciplines and data types) and data presentation (both online but also through 3D printing).

the foundation for integrated geoscientific research and training in Svalbard.

Acknowledgements

Financial support for the acquisition of the Festningen digital outcrop model was provided by the Ørnen project (Lundin Energy). The Svalbox project received direct funding or in-kind contribution from University of the Arctic, ARCEx – the Research Centre for Arctic Petroleum Research, the Norwegian CCS Research Centre, the Norwegian Research School for Petroleum, Svalbard Science Forum, iEarth and UNIS. UNIS sincerely appreciates academic licences of Petrel, the Blueback Toolbox and Agisoft provided by Schlumberger, Cegal and Agisoft, respectively. The Norwegian Petroleum Directorate kindly provided wireline log data from Ishøgda. We sincerely appreciate discussions, field and technical assistance by our colleagues, notably Snorre Olaussen, Tereza Mosočiová and Anna Sartell. Julian Janocha and Gareth Lord acquired the Selmaneset model. Simon Buckley and Conor Lewis from the VOG group uploaded the Festningen model to V3Geo. Finally, we sincerely appreciate the insightful, constructive and timely comments from the editor Gwenola Michaud, Dr Peter Rowbotham and Dr Jenny Garnham.

References

Bergen, K. J., Johnson, P. A., Maarten, V. and Beroza, G.C. [2019]. Machine learning for data-driven discovery in solid Earth geoscience. *Science* 363(6433), 10.1126/science.aau0323.

Betlem, P. and Senger, K. [2022] Svalbox-DOM_2020-0001_Festningen [Data set]. https://doi.org/10.11582/2022.00006.

Buckley, S.J., Howell, J.A., Enge, H.D. and Kurz, T.H. [2008]. Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. *Journal of the Geological Society* **165**(3), 625-638, 10.1144/0016-76492007-100.

Buckley, S.J., Howell, J.A., Naumann, N., Lewis, C., Chmielewska, M., Ringdal, K., Vanbiervliet, J., Tong, B., Mulelid-Tynes, O.S. and Foster, D. [2021]. V3Geo: A cloud-based repository for virtual 3D models in geoscience. *Geoscience Communication Discussions*, 1-27, doi.org/10.5194/gc-2021-30.

Buckley, S.J., Ringdal, K., Naumann, N., Dolva, B., Kurz, T.H., Howell, J.A. and Dewez, T.J. [2019]. LIME: Software for 3-D visualization, interpretation, and communication of virtual geoscience models. *Geosphere*, doi.org/10.1130/GES02002.1.

Cabello, P., Domínguez, D., Murillo-López, M.H., López-Blanco, M., García-Sellés, D., Cuevas, J. L., Marzo, M. and Arbués, P. [2018]. From conventional outcrop datasets and digital outcrop models to flow simulation in the Pont de Montanyana point-bar deposits (Ypresian, Southern Pyrenees). *Marine and Petroleum Geology*, **94**, 19-42,

Dallmann, W. [2015]. Geoscience Atlas of Svalbard. Norsk Polarinstitutt Rapportserie 148, 292, http://hdl.handle.net/11250/2580810.

Eiken, O. [1985]. Seismic mapping of the post-Caledonian strata in Svalbard. *Polar Research* 3(2), 167-176, 10.1111/j.1751-8369.1985.tb00505.x.

Grasby, S.E., Beauchamp, B., Bond, D.P., Wignall, P., Talavera, C., Galloway, J.M., Piepjohn, K., Reinhardt, L. and Blomeier, D. [2015] .Progressive environmental deterioration in northwestern Pangea leading to the latest Permian extinction. *Bulletin,* **127**(9-10), 1331-1347, doi.org/10.1130/B31197.1.

Grasby, S.E., Knies, J., Beauchamp, B., Bond, D.P., Wignall, P. and Sun, Y. [2020] .Global warming leads to Early Triassic nutrient stress across northern Pangea. *GSA Bulletin,* **132**(5-6), 943-954, doi.org/10.1130/B32036.1.

Grundvåg, S.-A., Jelby, M.E., Śliwińska, K.K., Nøhr-Hansen, H., Aadland, T., Sandvik, S.E., Tennvassås, I., Engen, T. and Olaussen, S. [2019]. Sedimentology and palynology of the Lower Cretaceous succession of central Spitsbergen: integration of subsurface and outcrop data. *Norwegian Journal of Geology,* **99**, 1-32, https://dx.doi.org/10.17850/njg006.

Henriksen, E., Ryseth, A.E., Larssen, G.B., Heide, T., Rønning, K., Sollid, K. and Stoupakova, A.V. [2011]. Chapter 10 Tectonostratigraphy of the greater Barents Sea: implications for petroleum systems. Arctic Petroleum Geology, A.M. Spencer, A.F. Embry, D.L. Gautier, A.V. Stoupakova and K. Sørensen (eds.), 163-195. The Geological Society, London, 10.1144/m35.10.

Hoel, A. and Orvin, A.K. [1937]. Das Festungsprofil auf Spitzbergen. I, Karbon-Kreide: Vermessungsresultate. https://brage.npolar.no/npolar-xmlui/bitstream/handle/11250/173612/Skrifter018.pdf?sequence=1.

Howell, J.A., Martinius, A.W. and Good, T.R. [2014]. The application of outcrop analogues in geological modelling: a review, present status and future outlook. Sediment-Body Geometry and Heterogeneity: Analogue Studies for Modelling the Subsurface, A.W. Martinius, J.A. Howell and T.R. Good (eds.), 1-25. Geological Society of London, London, https://doi.org/10.1144/SP387.12.

Hurum, J., Milàn, J., Hammer, O., Midtkandal, I., Amundsen, H. and Sæther, B. [2006]. Tracking polar dinosaurs-new finds from the Lower Cretaceous of Svalbard. *Norwegian Journal of Geology* , **86**, 397-402.

Larssen, K., Senger, K. and Grundvåg, S.-A. [2020]. Fracture characterization in Upper Permian carbonates in Spitsbergen: A workflow from digital outcrop to geo-model. *Marine and Petroleum Geology,* **122**, 104703, doi.org/10.1016/j.marpetgeo.2020.104703.

Lary, D.J., Alavi, A.H., Gandomi, A.H. and Walker, A.L. [2016] .Machine learning in geosciences and remote sensing. *Geoscience Frontiers,* **7**(1), 3-10, doi.org/10.1016/j.gsf.2015.07.003.

Lubrano-Lavadera, P., Senger, K., Mulrooney, M., Lecomte, I. and Kuehn, D. [2019]. Seismic modelling of metre-scale normal faults at a reservoir-cap rock interface in Central Spitsbergen, Svalbard: implications for CO2 storage. *Norwegian Journal of Geology*, 10.17850/njg003.

Luetzenburg, G., Kroon, A. and Bjørk, A.A. [2021]. Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences. Scientific reports, **11**(1), 1-9.

Marques Jr, A., Horota, R.K., de Souza, E.M., Lupssinskü, L., Rossa, P., Aires, A.S., Bachi, L., Veronez, M.R., Gonzaga Jr, L. and Cazarin, C.L. [2020]. Virtual and digital outcrops in the petroleum industry: A systematic review. *Earth-Science Reviews*, 103260, 10.1016/j.earscirev.2020.103260.

Mørk, A. and Grundvåg, S.-A. [2020]. Festningen - A 300-million-year journey through shoreline exposures of the Carboniferous and Mesozoic in 7 kilometers. 36, https://geologi.no/faglitteratur-boker/geologiske-guider/file/224-geological-guides-2020.

Mørk, A., Knarud, R. and Worsley, D. [1982]. Depositional and diagenetic environments of the Triassic and Lower Jurassic succession of Svalbard. Arctic geology and geophysics: proceedings of the Third International Symposium on Arctic Geology., A.F.E.H.R. Balkwill (ed.), 371-398. Canadian Society of Petroleum Geologists., Calgary.

Nagy, J. and Berge, S.H. [2008]. Micropalaeontological evidence of brackish water conditions during deposition of the Knorringfjellet Formation, Late Triassic–Early Jurassic, Spitsbergen. *Polar Research,* **27**(3), 413-427, doi.org/10.3402/polar.v27i3.6184.

Over, J.-S.R., Ritchie, A.C., Kranenburg, C.J., Brown, J.A., Buscombe, D.D., Noble, T., Sherwood, C.R., Warrick, J.A. and Wernette, P.A. [2021]. Processing coastal imagery with Agisoft Metashape Professional Edition, version 1.6 — Structure from motion workflow documentation. US Geological Survey, https://doi.org/10.3133/ofr20211039.

Rarity, F., Van Lanen, X., Hodgetts, D., Gawthorpe, R., Wilson, P., Fabuel-Perez, I. and Redfern, J. [2014]. LiDAR-based digital outcrops for sedimentological analysis: workflows and techniques. Geological Society, London, Special Publications, **387**(1), 153-183, 10.1144/SP387.5.

Schobben, M., Foster, W.J., Sleveland, A.R., Zuchuat, V., Svensen, H.H., Planke, S., Bond, D.P., Marcelis, F., Newton, R.J. and Wignall, P.B. [2020]. A nutrient control on marine anoxia during the end-Permian mass extinction. *Nature Geoscience,* **13**(9), 640-646,

Senger, K., Betlem, P., Birchall, T., Buckley, S.J., Coakley, B., Eide, C.H., Flaig, P.P., Forien, M., Galland, O., Gonzaga Jr, L., Jensen, M., Kurz, T., Lecomte, I., Mair, K., Malm, R., Mulrooney, M., Naumann, N., Nordmo, I., Nolde, N., Ogata, K., Rabbel, O., Schaaf, N.W. and Smyrak-Sikora, A. [2021a]. Using digital outcrops to make the high Arctic more accessible through the Svalbox database. *Journal of Geoscience Education,* **69**, 123-137, https://doi.org/10.1080/10899995.2020.1813865.

Senger, K., Betlem, P., Grundvåg, S.-A., Horota, R.K., Buckley, S.J., Smyrak-Sikora, A., Jochmann, M.M., Birchall, T., Janocha, J., Ogata, K., Kuckero, L., Johannessen, R.M., Lecomte, I., Cohen, S.M. and Olaussen, S. [2021b]. Teaching with digital geology in the high Arctic: opportunities and challenges. *Geoscience Communication*, 1-39, https://doi.org/10.5194/gc-4-399-2021.

Senger, K., Brugmans, P., Grundvåg, S.-A., Jochmann, M., Nøttvedt, A., Olaussen, S., Skotte, A. and Smyrak-Sikora, A. [2019]. Petroleum, coal and research drilling onshore Svalbard: a historical perspective. *Norwegian Journal of Geology*, 10.17850/njg99-3-1.

Vickers, M.L., Price, G.D., Jerrett, R.M., Sutton, P., Watkinson, M.P. and FitzPatrick, M. [2019]. The duration and magnitude of Cretaceous cool events: Evidence from the northern high latitudes. *Bulletin,* **131(**11-12), 1979-1994, doi.org/10.1130/B35074.1.

Vickers, M.L., Price, G.D., Jerrett, R.M. and Watkinson, M. [2016]. Stratigraphic and geochemical expression of Barremian-Aptian global climate change in Arctic Svalbard. *Geosphere,* **12**(5), 1594-1605, doi.org/10.1130/GES01344.1.

VizLab. [2022]. https://mosis.vizlab.cc/en; accessed 4.2.2022.

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., Peter A.C ’t Hoen, Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., Schaik, R. v., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., Lei, J. v. d., Mulligen, E. v., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J. and Mons, B. [2016]. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific data*, **3**(1), 1-9.