Digitising Svalbard’s geology: the Festningen digital outcrop model

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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 km² 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 CO₂. 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

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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 km² large area (14 km² onshore and 3 km² 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-
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 km² digital outcrop model (Figure 4; estimated total camera error: 3.57 m, ground resolution: 7.01 mm/pixel) relied on the drone-mounted GPS.

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 Table 1

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

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 connec-
tiveness 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 commu-
nity, 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

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**Figure 7** Putting the Festningen profile into a regional context by integration of published regional profiles (from Dallmann 2015) and two 20 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.
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


