Teaching with digital geology in the high Arctic: opportunities and challenges

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Abstract

The Covid-19 pandemic occurred at a time of major revolution in the geosciences – the era of digital geology. Digital outcrop models (DOMs) acquired from consumer drones, processed using user-friendly photogrammetric software and shared with the wider audience through online platforms are a cornerstone of this digital geological revolution. Integration of DOMs with other geoscientific data, such as geological maps, satellite imagery, terrain models, geophysical data and field observations strengthens their application in both research and education. Teaching geology with digital tools advances students' learning experience by providing access to ~~spectacular~~ high-quality outcrops, enhancing visualization of 3D geological structures and improving data integration. Similarly, active use of DOMs to integrate new field observations will facilitate more effective fieldwork and quantitative research. From a student's perspective, geo-referenced and scaled DOMs allow an improved appreciation of scale and of 3D architecture, a major threshold concept in geoscientific education.

~~In view of the Covid-19 pandemic,~~ DOMs allow to bring geoscientists to the outcrops digitally, which is particularly important in view of the Covid-19 pandemic that restricts travel and thus direct access to outcrops. At the University Centre in Svalbard (UNIS), located at 78°N in Longyearbyen in Arctic Norway, DOMs are actively used even in non-pandemic years, as the summer field season is short and not overlapping with the Bachelor "Arctic Geology" course package held from January to June each year. In 2017, we at UNIS developed a new course ('AG222: Integrated Geological Methods: from outcrop to geomodel') to encourage the use of emerging techniques like DOMs and data integration to solve authentic geoscientific challenges. In parallel, we have established the open access Svalbox geoscientific portal, which forms the backbone of the AG222 course activities and provides easy access to a growing number of DOMs, 360° imagery, subsurface data and published geoscientific data from Svalbard. Considering the rapid onset of the Covid-19 pandemic, the Svalbox portal and the pre-Covid work on digital techniques in AG222 allowed us to rapidly adapt and fulfill at least some of the

students' learning objectives during the pandemic. In this contribution, we provide an overview of the course development and share experiences from running the AG222 course and the Svalbox platform, both before and during the Covid-19 pandemic.

Introduction

From 13th of March 2020 until the summer break, all university-level teaching in Norway (including Longyearbyen, where the University Centre in Svalbard (UNIS) is located) was conducted fully digitally due to the Covid-19 pandemic. In Svalbard, this occurred at the worst possible time with respect to the geology bachelor course schedule, as the sun only returns to Longyearbyen on 8th of March after a long dark season. March and April represent the major spring field season when snowscooters can be used to access outcrops. In the years leading up to the pandemic we developed a new methods-focused Bachelor-level course at UNIS, "AG222: Integrated geological methods – from outcrop to geomodel", focusing on digital geological techniques in order to extend our field season digitally. This focus on enhancing the value of digital geological methods in education prior to the pandemic was instrumental during the transition to digital teaching of AG222 during the pandemic.

Digital outcrop models (DOMs) have been used for several decades, particularly by the petroleum industry with its need for quantitative data on reservoir architecture (Howell et al., 2014; Marques Jr et al., 2020). Initially, most DOMs were collected by ground- or helicopter-based Lidar (Light Detection and Ranging)lidar scanners (Hodgetts, 2013; Rittersbacher et al., 2013; Buckley et al., 2008), often requiring expensive equipment and significant processing resources, time and specialist skills. The emergence of structure-from-motion (SfM) photogrammetry (Westoby et al., 2012; e.g., Smith et al., 2016), essentially utilizing many overlapping images to construct a DOM, has led to mainstream adoption of DOMs in both teaching (e.g., Senger et al., 2020; Bond and Cawood, 2020) and research (e.g., Anell et al., 2016; Marques Jr et al., 2020; Rabbel et al., 2018). We consider this a major technology-driven revolution in the geosciences as introduced by Buckley et al. (2019a), similar in significance to the adoption of 3D seismic acquisition that revolutionized our understanding of the subsurface (Cartwright and Huuse, 2005).

To make full use of this digital geoscience revolution, we need to re-think how geology is conducted and taught, while maintaining focus on key skill sets required by geologists in today's society. Field-based skills acquired while in the field are central to any geoscientist's education (Mogk and Goodwin, 2012), with digital tools allowing more efficient field work. In addition, integrating DOMs into a regional geological context using complementary data sets, and harvesting these expanding data for quantitative studies, we can take the next step towards "big data geoscience" (e.g., Guo et al., 2014; Bergen et al., 2019). Importantly, we should bring this geoscience revolution to geoscience students at an early stage, by developing skills-oriented courses where tasks are authentic to real-life problems faced by professional geologists.

Actively participating in the digital geoscience revolution has several benefits, including improved accessibility for those that cannot participate in field work (Whitmeyer et al., 2020; Bond and Cawood, 2020), a prolonged field season (Senger and Nordmo, 2020), potential for field work preparation and thus more effective and targeted field work and reduction in associated environmental and economic costs of field campaigns. It should, however, be

stressed that geoscientific field work should not be purely digital. Participation in traditional field work and field excursions are fundamental aspects of becoming a geoscientist (Mogk and Goodwin, 2012; Kastens et al., 2009), and digital tools should, in our opinion, complement these, rather than replace them.

Scientific literature on the application of photogrammetry in geology increases ~~exponentially~~ rapidly (Fig. 1), in line with technological advances. More importantly is that DOMs are readily available to the global geoscientific community through a number of open access repositories such as e-Rock (https://www.e-rock.co.uk/; global coverage; Cawood and Bond, 2019), V3Geo (https://v3geo.com/; global coverage), Mosis HUB (https://mosis.vizlab.cc/xp/models; Brazil coverage), Virtual Australia (http://ausgeol.org/atlas; Australia coverage) or Svalbox (http://svalbox.no/; Svalbard coverage; Senger et al., 2020). All of these are useful for teaching purposes and have been heavily used during the Covid-19 pandemic, as they provide examples of a number of lithologies and structural styles that can serve as a backbone to digital teaching exercises.

An important challenge yet to be fully addressed is that while we as a geoscientific community ~~exponentially~~ collect more DOMs globally, actively using them for further work is hampered by varying standards, available metadata and access regulations to the actual models. Furthermore, utilizing DOMs to their full potential requires site-specific knowledge of the regional significance of the outcrop, thus often relying on geologists with local expertise and efficiently harvesting the sheer volume of scientific knowledge about a particular area such as Svalbard (Fig. 1).

From a broader perspective, we as educators also need to consider how best to train geoscientists to exploit the digital geoscience revolution to their advantage. The benefits are clear, but the challenges with numerous software (some open-source, but most proprietary and costly) and using cross-software workflows can also be daunting. In essence, we can ask ourselves the question of how to best teach digital geosciences, and whether we can teach it in an active and integrated fashion.

In this contribution, we share our experiences of teaching digital geosciences at UNIS, primarily related to a 15 ECTS bachelor-level course (AG222: Integrated Geological Methods: from outcrop to geomodel; ECTS = European Credit Transfer and Accumulation System; 60 ECTS = one full-time study year) offered annually since 2018 that actively uses the Svalbox geoscience platform. We outline our experience of both the course development and incremental optimization, including a fully digital field campaign organized in April 2020 during the Covid-19 pandemic. Finally, we identify knowledge gaps that should be addressed to maximize the experience from the Covid-19 pandemic to further improve geoscientific field teaching in the high Arctic.

The Svalbox geoscience platform
Svalbox, developed at UNIS since 2017, and introduced by Senger et al. (2020), is a platform that strives to integrate multi-physical and multi-scale geoscientific data from Svalbard for more effective teaching and research. Svalbox (Fig. 2; Table 1; Video 1 in supplementary material; Discover Svalbard's Geology with Svalbox) comprises both a public web front end sharing most of the openly accessible data (Video 2 in supplementary material; Svalbox: Introducing the Svalbox.no online map portal), and a UNIS-internal package integrating also

classified data in thematic Petrel projects (Video 3 in supplementary material; Svalbox - what is it and what data do we integrate?).

Most of the Svalbox elements can also be used by geoscience courses not run by UNIS, and our ambition is to generate high-quality datasets and educational material to bring Svalbard's exciting geological evolution to classrooms around the world.

The AG222 course: establishment and incremental optimization

Being based in Svalbard, an Arctic archipelago located at 74-81°N, the AG222 course had from the onset been designed with the extreme seasonal cycle in mind (Fig. 3; Fig. 4; https://youtu.be/Pjr-4L5zqE8). The "Integrated Geological Methods: from outcrop to geomodel" (AG222; Supplementary Table A) course was developed at UNIS in 2017 and was run annually from 2018 onwards. In 2018 and 2019, the course was run as planned from January to late May, with up to 20 students admitted each year and a significant field component (Senger et al., 2020). In 2020, the Covid-19 pandemic led to the second half of the course being run fully digitally with students dispersed throughout Europe. Only one day of fieldwork was possible, with the main field campaign to Billefjorden having to be run virtually (Smyrak-Sikora et al., 2020). In January 2021, the course started as a fully digital course but with students in Longyearbyen. Since no Covid-19 cases were reported from Svalbard until submission of this paper in mid-March 2021, some physical teaching was implemented at UNIS in February 2021 and field excursions were run as planned in March-April 2021.

The overall ambition central to the course development was to provide a new course actively using emerging digital geological techniques applied to geoscience challenges relevant to Svalbard, with the key outcome of developing the problem-solving skills required by geology graduates in their future careers, especially relevant in industry. An important component focuses on the integration of different techniques and data sources, which are important skill sets for professional geologists that who also need to act multi-disciplinary to solve real-life geological challenges. Furthermore, the course was designed to complement the existing course "The Tectonic and Sedimentary History of Svalbard" (AG209; (https://www.unis.no/course/ag-209-the-tectonic-and-sedimentary-history-of-svalbard/)) running at the same time, attended by the same students and visiting complementary field sites.

Transport to the localities is primarily by snowscooter, which often increases engagement for many students (see Supplementary Video 4; AG222 excursion @ UNIS - February 2020). The Billefjorden excursion involves a long (ca 4-5 hours) journey to the field area, relying on good visibility as it involves crossing major glaciers exposed to bad weather. Once the field area is reached a base camp is established in a hotel in Pyramiden, an abandoned coal mining settlement (Fig. 3). From Pyramiden, all localities within the entire Billefjorden Trough are easily accessible within short driving distance (see .gpx files with localities and route in supplementary material). Geological stops are typically up to one hour long, and summaries of the main learnings from the visited localities are conducted through student presentations once back in the sheltered base camp.

The AG222 course: case studies

All course modules and assessments in the AG222 course are designed with a strong ~~component~~ emphasis on real-world application – i.e. they should represent tasks that professional geologists working in the private or public sector may face in their future careers. There is no final exam, and the course grade reflects tasks conducted

155 throughout the semester, combining both group and individual assessments (Fig. 5). Table 4 provides an overview of the tools used by the students to tackle the assessments. In this section, we present the main course modules and associated assessments. Adequate material is provided in the supplementary material to allow implementation of these elsewhere. Naturally, the exercises are focused on Svalbard's geological record, but the concept can easily be applied in other areas. For educators and students not familiar with Svalbard's geological evolution, Electronic

160 appendix Table B2 provides a list of key literature.

Data mining and integration

AG222 starts in January, in the middle of the polar night. Before the light and sun return in mid-February and early March respectively (Fig. 4), the students familiarize themselves with the different tools (software and online

165 resources; see Table 3) and data sets they will be using throughout the semester. In parallel, the sister course AG209 introduces Svalbard's tectono-stratigraphic evolution and main concepts such as source-to-sink.

The exercises are built around practical tasks that are routinely used by geologists working in Svalbard – including planning field campaigns in different seasons (using geological maps, satellite imagery, oblique aerial images and DOMs), investigating what research has already been conducted in a given area (using literature and the

170 ResearchInSvalbard database) and integrating all available databases and tools (e.g., Svalbox, SvalSIM, StoryMaps, online resources). The skills acquired through the exercises are strengthened by regular student presentations to their peers, and generation of "how-to" videos shared through the SvalDocs Wiki platform (which builds up over time) and the course page on Microsoft Teams (which was implemented from 2020 and is only accessible for the current AG222 students). Furthermore, the rest of the AG222 course builds on the learned

175 practical skills and actively uses these in tasks later during the semester.

Digital models: acquisition, processing, interpretation and integration

Cost-effective georeferenced digital outcrop models (DOMs) are a breakthrough for geoscientific research and education, and naturally are included as a central part of the AG222 course. Students learn the entire workflow

180 from image acquisition to integration of DOMs with complementary data in the same area (Fig. 6). The dark season and snow cover prohibit ~~own~~ image acquisition of outcrops by the students, but photos of everyday objects and oblique images from TopoSvalbard are used as input data. In addition, photographs acquired during the summer field season by UNIS staff are provided for generating DOMs.

DOM processing is taught using a custom-build online e-learning module (https://unisvalbard.github.io/Geo-

185 SfM/landing-page.html) openly shared on the Github repository. Agisoft Metashape Professional is used for the SfM processing, and is also used for line interpretations in research projects at UNIS. In the AG222 course, models are exported to LIME (Buckley et al., 2019b) for interpretation and integration. In LIME, students make

measurements and observations using basic lines, orientation planes, panels and points of interest (see http://www.virtualoutcrop.com/resources/videos for details). Later, they can integrate terrain models, maps and remote sensing imagery to give regional context and appreciate the variations in scale between different datasets. They also create panel interpretations (Buckley et al., 2019) and present a characterisation of their selected DOM in group presentations. The Svalbox database (Senger et al., 2020) provides the students with an overview of the available DOMs from Svalbard and allows them to access these for their research projects. DOMs are all available on the Svalbox online portal (www.svalbox.no/map) and selected ones are also uploaded to the V3Geo, including the "flagship" DOM of Festningen (https://v3geo.com/model/226).

Virtual field trips

Virtual field trips (VFTs) integrate numerous elements (digital outcrop models, publications, 360 imagery, photos, geological maps, satellite imagery, etc.) within a geological story line suited for a specific target audience. VFTs can be actively presented to an audience or made accessible for individuals to follow at their own pace. Building a VFT is as rewarding as following one, as it fosters creativity and group work. Furthermore, the oral presentation of the VFT by the student groups simulates authentic experiences of presenting at international conferences.

A central assignment in AG222 (25% of course grade) involves the students developing a VFT to a given location and presenting it to a wider audience (i.e. the AG222 class, AG222 guest lecturers and UNIS geology staff). The task is conducted from the onset of the course and finalizes by the end of February when the light slowly returns to Longyearbyen. As such, the students only use provided material and data to develop a catchy and creative VFT. From 2018 to 2020, VFTs were organized as in-person presentations, where all elements were linked through a standard presentation (PowerPoint or Prezi). From 2021, we have adopted the online ArcGIS StoryMaps approach to develop the VFTs. StoryMaps is a commercial product, but a site license is available at UNIS for its unlimited usage. This allows more creativity with respect to directly embedding DOMs, videos and other central elements. As a further benefit, the resulting VFTs are permanently available on the Svalbox portal (http://www.svalbox.no/virtual-field-trips/; Table 5) for further exposure and to contribute to a growing VFT database from Svalbard. The supplementary material provides the key public-domain resources and tools required to design Svalbard VFT experience.

Synthetic seismic

Seismic modelling allows the direct correlation of outcrops with seismic data, aiding to quantify what geological features are visible on the latter. By creating geomodels from digital outcrop models, students also truly appreciate several factors that control seismic images. Building geomodels involves conducting line interpretations on digital outcrops to establish the structures, then assigning elastic properties (P- and S-wave velocity and density) to these from literature or borehole data crossing the same stratigraphic interval of interest. Once both structures and elastic properties are in place, seismic modelling is applied (e.g., Rabbel et al., 2018; Anell et al., 2016). Noise is usually also added for more realistic results (Lubrano-Lavadera et al., 2019). The synthetic seismic profiles are then overlain on the DOM and class discussions focus on understanding what geological features are discernible, and how seismic acquisition parameters (primarily frequency and illumination angle) affect seismic imaging.

In AG222, the Triassic succession at Kvalpynten in south-western Edgeøya (https://v3geo.com/model/90; Anell et al., 2016; Smyrak-Sikora et al., 2020) was primarily used from 2018 to 2020 as ~~an excellent~~a very-well exposed and well-studied case study (Fig. 7). The "seismic-scale" outcrop displays two contrasting geological features. The lower part of the outcrop is dominated by growth-faults with small half-grabens infilled by siliciclastic syn-sedimentary deposits. In the upper part, very low angle clinoforms related to the progradation of the world's largest delta plain in the Triassic (Klausen et al., 2019) are barely apparent even at the ca. 7 km long outcrop.

Billefjorden claim application

The license claim application is an intensive group assessment worth 30% of the AG222 grade, conducted in an intensive 3.5 week period building around the main 4-day AG222 field excursion to the Billefjorden Trough. The application follows a strict template, as do authentic license applications, and challenges the students to compile a convincing overview of the petroleum system elements to secure a fictive claim in the field area (Fig. 8). Furthermore, an exact drilling location and well prognosis to 1300-1600 m depth must be provided, along with sub-surface correlations and environmental considerations relating to petroleum exploration of this sensitive area.

This assignment is by far the most authentic of all AG222 tasks, as the only oil discovery in Svalbard was reported from the area, a consequence of coal exploration by the Russian company Trust Arktikugol in the 1990s (Senger et al., 2019). Indeed, there were concrete plans as late as 2004 to drill a serious petroleum exploration borehole in the area (Senger et al., 2019). Obviously, these plans never materialized, but the AG222 students can experience this authenticity, and make full use of their geological understanding to compete between the groups for the best overall license claim application.

The students integrate pre-existing material to learn as much as they can about the Billefjorden Trough prior to the field excursion, including exposure to DOMs from summer field work and a comprehensive Petrel project of the basin (including wells, published cross-sections, digital terrain model, satellite imagery, geological maps). During the field campaign, students get both a basin-scale exposure at overview stops, but also collect samples and information (structural and sedimentological data) to be used in their application. The digital field notebook (Senger and Nordmo, 2020) is used to organize each group's field data, and the resulting FieldMove project is a compulsory appendix to the license claim application.

Near-town geology: drill core & outcrop sedimentology and structures

A core shed near UNIS stores more than 60 km of drill cores collected by the local mining company SNSK for coal exploration, and for scientific purposes (e.g., UNIS CO_2 lab; Olaussen et al., 2019). The stratigraphy covers the successions outcropping in the mountain sides near Longyearbyen. Since geologists from the mining company have contributed to teaching at UNIS for almost two decades, it was natural to make this unique material available for student learning. Accompanied by the company geologist, students visit the shed to get first-hand knowledge about diamond drilling in the high Arctic, and sedimentary drill core logging. They practice detailed logging of cores and logging under time pressure, role-playing that bad weather is coming and the helicopter waiting to pick them up, the latter often the case for real Arctic drill site geologists. These exercises help them to understand the

geology of the surrounding mountain, and they build the basis for later field-logging exercises, be it outcrop scale or making rough logs of mountain sides from the distance.

265 By early May, the snow begins to melt and outcrops near Longyearbyen allows for conducting some meaningful fieldwork along one of Svalbard's arguably best exposures: the c. 2 km continuous outcrop transect between Longyearbyen and the airport. The transect excellently exposes a succession of alternating sandstones, siltstones and shales of Early Cretaceous age, thus enabling high-resolution bed-to-bed scale investigations, as well as lateral tracing and mapping of depositional elements. In addition, c. 4.5 km of drill cores are available from parts of the

270 Mesozoic succession drilled by the UNIS CO_2 lab project (Olaussen et al., 2019). These cores penetrate the same succession that is exposed in the Flyplassveien outcrop. The combination of outcrops and drill cores allow for a detailed and integrated sedimentological and structural characterization of the investigated succession. The students focus on and practice various methods for acquiring and presenting sedimentological and structural data. Structural data are for example collected both with a traditional compass and by using digital tools like tablets and

275 smartphones (Novakova and Pavlis, 2017). In recent years, selected drill cores are digitized using SfM photogrammetry (Betlem et al., 2020b) and shared on Svalbox.

The collected scanline data are discussed in regard to the mechanical stratigraphy of the succession, particularly focusing on how bed thickness and lithology correlate with fracture intensity. In addition, field data are integrated with DOM data to extend the area of investigation to include the inaccessible parts of the outcrop. This also

280 increases the length of the field season that is notoriously short in the high Arctic.

Paleoclimate drilling poster presentation

Svalbard's geological record provides a unique window into deep-time paleoclimatic events of global significance (Senger et al., 2021). The Permian-Triassic boundary (P-Tr; Zuchuat et al., 2020) and the Paleocene-Eocene

285 Thermal Maximum (PETM; Dypvik et al., 2011) are just two examples of globally significant events preserved in Svalbard's rock record and studied in detail in drill cores from Svalbard. The P-Tr boundary was targeted by the last drilling in Svalbard, with two ca. 100 m deep research boreholes drilled and fully cored at Deltadalen in 2014 (Zuchuat et al., 2020).

The AG222 students finalize the course with an individual poster presentation that presents a "Deltadalen-style"

290 drilling proposal for a 100-200 m deep paleoclimate research borehole to target an assigned interval of interest (Snowball Earth; end Permian mass extinction; Early Cretaceous oceanic anoxic events; PETM). As with the petroleum drilling in Billefjorden, the students need to utilize all their skill sets to find a suitable location, and propose a realistic concrete target including a well prognosis. The assignment is individual, and its presentation at the final day of the AG222 course provides an authentic experience in presenting posters at scientific conferences.

295 **Discussion**

Digital outcrop models – a game changer for digital teaching

DOMs are in our opinion a cornerstone of the ongoing geoscience revolution and a game changer for digital geoscience teaching methods (Fig. 9). DOMs are multi-scaled features, and thus allow the easy appreciation of

resolution (i.e., pixel resolution, in other words the size of the smallest discernible objects), scale (i.e., size of the DOM) and perspective (i.e., viewing angle and exaggeration). DOMs can be generated across all scales, from seismic-scale outcrops to high-resolution drill core or hand sample models, and facilitate quantitative geology, including unprecedented possibilities for making realistic outcrop-based geological models (e.g., Larssen et al., 2020). Integration of DOMs with shallow geophysical data, e.g Ground-Penetrating Radar (GPR), also opens up to "see" geology beyond the outcrop, as illustrated with the paleokarst at Fortet (Supplementary video 5; The Billefjorden Trough STOP 6- update) (Janocha et al., 2020). Along with the explosion in cost-effective DOM acquisition from drones, the ease of sharing them with the global geoscience community through a multitude of 3D platforms (e.g., Sketchfab or V3Geo) and rendering libraries (e.g., potree- or Unity) truly opens up for global digital geology teaching.

DOMs complement traditional field data collection by facilitating data acquisition in inaccessible areas, provide greater structural data sampling and reduce time spent in the field (Nesbit et al., 2020; Pringle et al., 2006; McCaffrey et al., 2010). Furthermore, DOMs are ideal for training and teaching geology, as they allow appreciation of structures from different perspectives and vertical exaggerations, student-teacher discussions in a controlled indoor environment and (digital) accessibility to the field irrespective of the participants field experience, economic and cultural background.

DOMs, particularly when derived from drone-based photographs, make inaccessible outcrops safely accessible without the risk of rock fall, avalanches, climate issues, steep and rocky terrains or wildlife (e.g., polar bears, rattlesnakes). Precisely acquired DOMs allow geologists to extract and present quantitative and qualitative geological information and detailed measurements without the need to directly access them (Larssen et al., 2020; Marques Jr et al., 2020; Senger et al., 2015a; Nesbit et al., 2020; Nesbit et al., 2018). This approach increases the areas from which measurements can be made, which means that more statistical information can be collected, increasing the sample size and therefore reducing errors in statistical analysis (Fabuel-Perez et al., 2010; García-Sellés et al., 2011; Hodgetts, 2013).

In the same way, new attributes can be generated to highlight subtle features, helping in the interpretation by providing the basis for automated mapping approaches (McCaffrey et al., 2005; McCaffrey et al., 2010). These either reduce the time needed for fieldwork, or make fieldwork more efficient with more data acquired over the same time interval. For comparison, Ogata et al. (2014) present > 9000 structural measurements of fractures collected on a sandstone in Svalbard over a 1-month field period, while recently acquired DOMs in the same area would exponentially reduce the time needed to collect the same data. The reduced cost of fieldwork by active use DOMs and VFTs is also considerable, both in industry and academia. This is especially relevant when entire teams should investigate outcrops together, and discuss while observing the outcrop. However, DOMs are still not a replacement for traditional field trips, but a tool that can improve the field experience (Hodgetts, 2013), making it an efficient way to integrate and visualize multi-scalar surface and sub-surface rock data in desktop applications. The increased use of immersive Virtual Reality (iVR) already provides authentic digital field experiences (Gonzaga et al., 2018), and only the resolution and spatial limits of individual DOMs set the boundaries of what is possible.

Course development & integration with Svalbox portal

The AG222 course was developed in parallel with the Svalbox portal, and this synergy will be optimized also in the coming years (Fig. 10). The skills-based course requires relevant and authentic data sets for the authentic experiences, which is provided through Svalbox. On the other hand, the AG222 course provides content to the Svalbox portal, in particular virtual field trips developed by both staff and students. Similarly, UNIS-affiliated research projects including MSc and PhD students contribute data sets to Svalbox, in particular DOMs and 360° images. Over time, we envision that this will lead to an exponentiala rapid increase in DOMs from Svalbard openly available for the global geoscience community.

It must be noted that the AG222 course is inspired by state-of-the-art training offered in the petroleum industry, with expert teams working together to solve authentic "real-world" problems. It is thus imperative that the skills the students acquire as part of the course are applicable in the students' future careers irrespective of sector. In addition to the technical skills learnt during the course, extra skills such as data management, group work and handling intensive periods with heavy workloads are important elements to make the AG222 course as authentic as possible.

Field-based training for the petroleum industry and communication to the broader society

We can regard Svalbard as the exposed part of the subsurface of the Barents Sea, with ongoing petroleum exploration and production. UNIS has over the past decade run excursions for the oil industry, particularly to

localities exhibiting Carboniferous to Lower Cretaceous strata. Those strata are linked to the proven reservoirs and source rocks in the efficient petroleum systems in the southwestern Barents Sea petroleum province. The main purpose of these field-based educational expeditions for the industry is to train the geological and geophysical staff in the regional overview of the basins, tectonism, architecture and scale of reservoirs. The excursion/field trip is run by a medium sized ship capable of accommodating 20 passengers. Although geological guides are handed out, presentations are given in the evening of what to see the next day and are repeated the next morning, it is a challenging to present the localities as relevant for the normal "work station scale" (e.g., Petrel, Landmark etc.) at the office. However, if the participants upfront on their own computer play with a DOM of the specific outcrop to be visited it will be possible to better understand the scale and architecture of the geology to be visited. We thus foresee enhanced use of Svalbox in such targeted field campaigns, particularly when the Covid-19 pandemic passes and such excursions once again become feasible.

Covid-19 implications

On the 13th of March 2020, the Covid-19 pandemic forced the cancellation of all fieldwork at UNIS. 17 bachelor students were able to continue remotely as courses running at the time were continued digitally. The original plan included a four-day long snowmobile fieldtrip to the Carboniferous rift basin located in central Spitsbergen. The structure of the excursion was kept as close to the original plan as possible (Fig.11). Instead of the work at a real outcrop, students were tasked with preparing "digital geological stops" of assigned sites throughout the basin and present these to the entire class through a publicly available video (Green box in Fig. 11; See the playlist here: https://www.youtube.com/watch?v=_Izk4yhEN2Y&list=PLaERIU24EpWf93UbEB701vFTqwBPG6CpY). The videos included DOMs from Svalbox, geological maps, aerial images, Google Earth overviews, georeferenced photos and measurements and notes from FieldMove projects compiled by students taking the course in previous years. Following the presentation of these field guides, additional information and discussions were facilitated by the lecturers. The students, in groups of 3-4, were tasked to identify potential hydrocarbon prospects, and apply for a fictional claim application in Billefjorden, as described above.

The qualitative feedback collected from the students and teachers clearly points out that the virtual field excursions cannot replace real field experience. Principal geological tests such as Mohs hardness tests, grain/crystal size analysis, or ground-truthing structural orientation measurements, which are a foundation of bachelor-level courses, cannot be performed virtually. Virtual field excursions can, however, contribute to the field-based education and serve as an introduction to the study area and function as a substitute for snow-covered or inaccessible localities or when a planned field excursion needs to be adapted to harsh weather conditions. Ultimately, our experience suggests that there are real benefits to virtual excursions only if it is combined with real field work of the same or comparable geology.

The sister course AG-209 was also forced to adapt to the Covid-19 situation. Term projects based on field research were changed to literature research term projects, and the final assessment was changed from a graded written exam to pass/fail with an oral exam. In addition, the learning outcomes had to be changed, mainly due to the fact that education of Arctic field geologists is impossible online, and the few field days students have had by then were only introductory. Logging and interpretation exercises, based on photographs of drill cores and outcrops instead of real rocks, were performed with surprisingly good outcome. This result would however not have been

~~possible without the thorough introduction to sedimentary logging and describing of rocks which had been done in field and classroom prior to the Covid-19 lockdown and the students' prior skills.~~

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Future perspectives

The AG222 course will continue to be offered every year and thus allows sustainable and incremental optimization through integrating emerging tools. At the moment, we are developing open access online modules for all the course modules, inspired by the successful Geo-SfM course module (Table 1). In addition, we are continuously

420 testing new tools, for instance smartphones and tablet with in-built Lidar scanners (e.g., iPhone 12 Pro, 3D printers, VR technologies, thermal cameras, drone-mounted sensors) to push the boundaries of digital geological techniques. Perhaps more importantly than testing and sharing experiences from new hardware are the efforts to outline best practice documents for the many important cross-software workflows, along the from outcrop to geomodel framework.

425 Our overall vision is that the Svalbox platform will facilitate free and easy access to all the collected data elements. This innovative approach building on FAIR (i.e. findable, accessible, inter-operable and re-usable) data principles (Mons et al., 2017) and the open data movement will exponentially enhance the use of Svalbox DOMs beyond UNIS and contribute to squeezing out more information from already collected data. This approach applies not just to the data sets, but also tools to be used. Both StoryMaps and Petrel are licensed software, though with

430 academic rates (Petrel is, for instance, at the time being available for free for academic institutions like UNIS). In the future, we envision testing and potentially adopting open-source solutions for the entire Svalbox value chain. The ongoing digitization efforts of the subsurface (e.g., Nguyen et al., 2020), of vital importance for many geo-energy applications (e.g., petroleum exploration & production, CO_2 storage, geothermal energy, gas and nuclear waste storage), will be able to use DOMs from a range of lithologies to test and train algorithms to facilitate the

435 (semi-)automatic interpretation of the outcrops, including machine learning and big data analyses. Furthermore, geoscientists will ideally be able to put together all Svalbox elements into thematic virtual field trips at a click of a button. Similarly, educators at UNIS and beyond can already now use Svalbox elements to generate online and class-based course modules. As an example, UNIS staff is currently involved in developing two course modules, "Deep-time paleoclimate in the Svalbard rock record" and "Petroleum systems of Svalbard", to be offered also to

440 students not physically in Svalbard.

Applications of Svalbox beyond Svalbard

The Svalbox concept can, in theory, be established also in other locations worldwide. The main requirements are access to high-quality outcrops with varied geological features, complementary surface and subsurface data, and

445 mid- to long-term funding to allow not just development but also regular updates. Clearly, programming skills are required in the team, together with local geological knowledge and data management skills. Ideally, a Svalbox-type project has a full-time data manager who can conduct regular data updates and develop the project over a longer-term. At present, Svalbox is essentially run on the side of other teaching and research duties, with key expertise covered by temporary PhD student duty hours, which is considered the biggest risk in terms of the

450 project's sustainability over the long term. Nonetheless, the current focus on digitization across the society, access

to open access data and focus on emerging technologies, promises opportunities to seek longer-term funding also with longer-term staffing.

A large part of Svalbox' success relates to the direct linkage with the AG-222 course and its students, who still represent the main user group of the portal. The students of AG-222 have a varied background from different Norwegian, Nordic and international universities. The students are introduced to state-of-the-art technology and teaching methods in the BSc-level AG-222, which may inspire and influence their future career choices and skill sets for example when pursuing a MSc project. Ideally, the AG-222 students may also bring some new knowledge and skills back to their home institutions, and thus contribute to broadening and advancing this type of technology-based and research-oriented teaching beyond Svalbard.

Furthermore, the strength of Svalbox compared to other DOM repositories in the world lies in the direct integration of DOMs with other geoscientific data. As far as we are aware, there are no other databases with such a rich (and growing) data set that integrates both DOMs and other geoscientific data. The geological playground of Svalbard with its rich history of coal and hydrocarbon exploration (Senger et al., 2019) and the well-exposed and stratigraphically diverse outcrops, provides a unique opportunity to develop Svalbard into a digital teaching and training hub for use beyond UNIS. For instance, the introduction of Svalbard's geology or the Festningen section is already an element of various courses at Norwegian mainland universities. In addition, Svalbox is already a valuable tool for planning fieldwork for bachelor and master students doing data collection for their thesis projects, and for national and international researchers that regularly visit the archipelago.

Summary and conclusion

In this contribution, we have outlined a Bachelor-level course on integrated geological methods developed at the world's northernmost university in Longyearbyen, Svalbard. The focus on digital tools, and in particular digital outcrops, not only extends the short Arctic field season, but also facilitated running the second half of the course fully digitally during the global Covid-19 pandemic in 2020.

We have provided an overview of the main course elements. We conclude that the digital geoscience revolution is among us and that we as educators need to embrace it – not to replace traditional fieldwork, but to complement it and exploit the synergies. There is no better place in the world than Svalbard to do this – as digital geology also significantly enhances our field season, and the geology of Svalbard is truly a playground for any geologist. The Svalbox portal is our contribution to open up this playground to the global geoscientific community.

Acknowledgements

The AG222 course is fully financed by UNIS, with significant course and Svalbox development costs financed through numerous co-operation grants from the University of the Arctic (UArctic). Digital outcrop models freely available on Svalbox are acquired using both UNIS internal funds and external projects, notably the Research Centre for Arctic Petroleum Exploration (ARCEx), the Norwegian CCS center (NCCS), the Suprabasins project led by the University of Oslo and the Petroleum Research School of Norway (NfiP). The iEarth Centre for

Integrated Earth Science Education provided seed funds to develop a virtual field trip to Festningen. The VOG Group at NORCE added a selection of Svalbox models to the V3Geo portal. We sincerely appreciate all feedback from UNIS colleagues and data sharing from MSc and PhD students and – of course – all the students of the AG222 course at UNIS over the years.

490 **Data availability**

Digital outcrop models available via www.svalbox.no, and Svalbox Petrel projects available from Kim Senger for non-commercial projects.

Code availability

495 Available via Svalbox GitHub repository, https://github.com/svalbox?language=python

Author contribution

Conceptualization - KS

Data curation – PB, TB, JJ, KS

Funding acquisition – KS, IL, SB, SO

500 Software – PB, SB

Visualization – KS, RKH, AS, TB, JJ, LK, RMJ

Writing – original draft preparation - KS

Writing – review & editing – KS, PB, SAG, RKH, SJB, AS, MMJ, TB, JJ, KO, LK, RMJ, IL, SMC, SO

Competing interests

505 The authors declare that they have no conflict of interest.

Tables

Table 1: Overview of central elements collectively comprising Svalbox elements.

Main element/Sub-element	Purpose	Data type	Accessibility	Reference/link
SvalDocs	Provide accessible documentation on how to use Svalbox, and a platform to share documents generated through Svalbox			
Workflows	Best practice for software, data acquisition	Documentation	Internally at UNIS	

Teaching material/e-learning	Relevant exercises and full course modules	Course material	Openly accessible	https://unisvalbard.github.io/Geo-SfM/landing-page.html
Virtual field trips	Storytelling based on Svalbox data elements	Stories	Openly accessible	http://www.svalbox.no/virtual-field-trips/
Literature	Dynamically updated list of literature included in Svalbox	Articles, theses, documents	Openly accessible	http://www.svalbox.no/bibliography/
Case studies	Actively use Svalbox in research projects	Articles, theses	Openly accessible	Published case studies (Janocha et al., 2020; Larssen et al., 2020), compiled on http://www.svalbox.no/publications/
Conference presentations and webinars	Promote and market Svalbox and its applications	Presentations, webinars	Openly accessible	Example from iEarth digital forum: https://iearth.no/en/2020/06/19/iearth-digital-learning-forum-svalbox/
Videos (Svalbox YouTube channel)	Promote and market Svalbox and its applications	Videos	Openly accessible	https://www.youtube.com/channel/UCQ7tTHrKaKSBB7fxUpnabeQ
Fileserver (SvalFiles)	Robust storage of all Svalbox data			
Acquired data	Systematically acquire DOMs of all key outcrops in Svalbard	Photographs and processed DOMs	Openly accessible	http://www.svalbox.no/outcrops/
	Sample and drill core models	Photographs and processed models	Openly accessible	Betlem et al. (2020b)
	Provide overview imagery from drone or handheld 360 cameras	360 degree imagery (photos and videos)	Openly accessible	http://www.svalbox.no/map/ https://www.youtube.com/watch?v=w1XHoM1BlCM&feature=youtu.be
	Acquire shallow geophysics	ERT and GPR, including integrated with DOMs	Internally at UNIS	Janocha et al (2020)
	Documentation of field campaigns	FieldMove projects, GPX tracks	Internally at UNIS	GPX tracks on SvalGIS
Integrated data	Place DOMs and own observations in a regional perspective	Borehole data	Internally at UNIS, borehole locations openly accessible via website	Petroleum and UNIS CO$_2$ lab research boreholes (Senger et al., 2019; Olaussen et al., 2019)
		Regional terrain, topography and satellite data	Streamed from NPI, openly accessible	https://geodata.npolar.no/
		Publications, including GeoTiffs, profiles and interpreted seismic	Internally at UNIS	Dallmann (2015), growing list of included publications on Svalbox website (http://www.svalbox.no/bibliography/)

	Seismic, EM	Internally at UNIS, profile locations openly accessible via website	e.g., Beka et al. (2017)
	Sedimentary logs	Internally at UNIS, log locations openly accessible via website	www.svalbox.no/map
GIS server (SvalGIS)	Sharing of georeferenced data and metadata internally and externally through Svalbox.no		
	DOMs	Openly accessible	www.svalbox.no/map
	360 imagery	Openly accessible	www.svalbox.no/map
	Borehole locations	Openly accessible	www.svalbox.no/map
	Geophysical profiles	Openly accessible	www.svalbox.no/map
	DOMs on external repositories	Open access on partner repositories	https://v3geo.com/model/226

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Table 2: Overview of the AG222 course modules.

Course module		Overall learning outcomes	Data and tools	Assessments in AG222
1	Data mining and integration	Learn to use Svalbox portal, and find relevant data sets Document and use workflows	Svalbox, online resources, SvalSIM, Petrel	Virtual field trip Practical exercises
2	Digital models	Learn to acquire, process and interpret digital models	Agisoft Metashape, LIME, Svalbox and V3Geo	Practical exercises Virtual field trip License claim application
3	Wireline logs, geophysics & synthetic seismic	Learn what different geophysical and well log methods are sensitive to Bridge the gap from outcrop to geophysics through seismic modelling	SeisRoX, Petrel	Practical exercises
4	Mechanical stratigraphy	Learn to collect own structural and sedimentological data from drill cores and outcrops	Fieldwork, cores, Svalbox	Scientific poster presented in a seminar

Table 3: Overview of the key assessments in AG222

Course assessment		Purpose	Tools used	Group/ Individual	Contribution to course grade and grading
1	Practical exercises	Learning skills by actively learning Keeping track of activity Use and document workflows	Svalbox, qGIS, ArcGIS, SvalSIM, StoryMaps, LIME, Petrel, online resources	I	20% pass/fail

2	Virtual field trip	Build – in a team of experts – a virtual field trip to an assigned locality with an enchanting storyline Be creative, innovative and get to know your group	Primarily StoryMaps, with components from assessment 1	G	25% A-F
3	License claim application	Play the "oil game" and find the best place to drill for petroleum in Billefjorden Maximize your field experience by collecting own data to complement pre-field work digital work	Petrel, FieldMove, field geology	G	30% A-F
4	Scientific poster	How did climate change in the geological past? Where in Svalbard would you drill to conduct further paleoclimatic research?	Components from assessment 1	I	25% A-F

515   **Table 4**: Overview of key resources, datasets and software used in the AG222 course

Resource	Course module	Accessibility	Used in Covid-19-related digital teaching?	Reference/Source
Svalbox online portal	Data mining & integration	Anywhere with internet	Yes	Senger et al. (2020)
Svalbox Petrel projects	Data mining & integration	UNIS PC	Used in physical teaching by students, but only by lecturers in digital teaching	Senger et al. (2020)
Svalbox GIS projects (ArcGIS and QGIS)	Data mining & integration	UNIS network	Yes	Senger et al. (2020) www.svalbox.no/map
Online geospatial resources	Data mining & integration	Anywhere with internet	Yes	https://toposvalbard.npolar.no/ https://geokart.npolar.no/Html5Viewer/index.html?viewer=Svalbardkartet https://researchinsvalbard.no/ http://www.svalbox.no/ https://factmaps.npd.no/factmaps/3_0/ https://geodata.npolar.no/
SvalSIM	Data mining & integration	Anywhere	Yes, in both years	Saether et al. (2004)
Agisoft Metashape	Digital models	UNIS PC	Yes, the session was held in February	Janocha et al. (2020)
LIME	Digital models	Anywhere	Yes, the LIME session was held in February. In person in 2020, and hybrid (guest lecturer digital, students in person) in 2021	Buckley et al. (2019b)
e-learning modules	Digital models	Anywhere with internet	Yes, in 2021	https://unisvalbard.github.io/Geo-SfM/landing-page.html Betlem et al. (2020a)
Smartphone/ iPad apps		Anywhere	Only for initial part	http://www.svalbox.no/software-apps/
Digital field notebook		Anywhere	No (but data collected in 2019 was provided)	Senger and Nordmo (2020)

Table 5: Examples of virtual field trips (VFTs) available on Svalbox

VFT title	Purpose	URL
Repository of virtual field trips	Access point for VFTs on the Svalbox portal	http://www.svalbox.no/virtual-field-trips/
Geology of Svalbard	Main landing page for Svalbox VFTs/Journeys	https://storymaps.arcgis.com/stories/36cf2935a6754422bba794edeea05b9f
Outcrop of the week - Festningen	Short teacher-provided VFT to familiarize students with StoryMaps features	https://storymaps.arcgis.com/stories/bb3fa994b60d44a9b1312e6c2784957c
Discovering the fossilized world of Festningen	Teacher-provided example of a longer VFT	https://storymaps.arcgis.com/stories/5efc4f9559c348f796e643b965a5b5e9

520 **Electronic supplements**

Videos:

AG222 course overview: https://www.youtube.com/watch?v=Pjr-4L5zqE8

Svalbox overview video: (Discover Svalbard's Geology with Svalbox)

360 degree video from 2020 Botneheia excursion (Rafael; AG222 excursion @ UNIS - February 2020)

525 GPS tracks of AG222 excursions in 2018 and 2019 (.gpx tracks)

Digital outcrop models available via www.svalbox.no/map, some available via www.V3Geo.com

Electronic Appendix Supplementary Table A1: Key parameters of the presented AG222 course

Course requirements:	60 ECTS within general natural science, of which 30 ECTS within the field of geology/geosciences. Enrollment in a programme at Bachelor level.
Academic content:	The geological history of the Svalbard archipelago is a story of how tectonic and climatic processes have affected sedimentation since the Caledonian orogeny, and serves as a "window" to the Barents shelf hydrocarbon province to the south. The sparsely vegetated, well exposed and in places well-studied outcrops provide a unique opportunity for entry-level geologists to get an understanding of how geological field data are collected in the field and analysed in the office. In addition, geophysical data are integrated to enhance the holistic understanding of a particular area. Authenticity is stressed throughout the course, with practical problems to solve resolving the numerous fields requiring the robust characterization of the subsurface, including coal mining, geological CO_2 storage, hydrocarbon exploration, underground gas storage, geothermal exploitation, ore exploration etc.
Learning outcomes:	Upon completing the course, the students will be able to conduct focused geological field data collection in small groups, be familiar and use a broad range of geological and geophysical methods, and actively use these data to produce a realistic geological model of the subsurface. **Knowledge** *Upon completing the course, the students will:* • develop a basic understanding of geological field mapping techniques (e.g., stratigraphic and structural mapping at outcrop and core scale) • develop a basic understanding of geophysical data interpretation techniques (e.g., seismic, electric methods, wireline log interpretation) • actively use modern tools (e.g., photogrammetry to construct virtual outcrops, industry-standard software for both integration and seismic modelling) to link geology and geophysics together • be introduced to emerging technologies relevant for geological fieldwork, including digital outcrops, virtual reality and integration of various data. **Skills** *Upon completing the course, the students will be able to:* • be able to work together to solve realistic and authentic subsurface characterization problems • improve the understanding of the geology of an area by collecting relevant new data in the field and integrating it with pre-existing information and present their findings to the class

	• get an authentic experience of how subsurface characterization is conducted in practice, where the key uncertainties lie and how relevant geological know-how can directly or indirectly improve the geomodel. **General competences** *Upon completing the course, the students will:* • gain first-hand experience of actively working both individually and in small groups • improve the presentation skills by presenting their work to their peers and creatively tackling the set problems.
Learning activities:	The course will be very practical oriented, with a relatively small number of introduction and overview lectures complemented by practical exercises carried out by the students both individually and in small groups. These exercises will focus on sedimentology and structural analysis (of cores and near-town outcrops), geophysics (seismic and non-seismic interpretation), well log interpretation, geomodelling and data integration. Students will participate in a whole class excursion in Svalbard where each group will be presenting a selected geological field site to their peers. **Total lecture hours:** 16 hours **Total practical exercises/PC lab work:** 60 hours **Fieldwork/excursions:** ca 3 days with overnight stay, up to 3 day-excursions **Course length**: 20 weeks
Course assessment:	All compulsory learning activities (i.e. Excursions and group field work) must be approved in order to be registered for the final assessments. **Assessment method:** **Percentage of final grade:** Practical exercises (individual work) 20% Digital field report from excursion (group work) 30% Presentation of virtual field trip (group work) 25% Presentation of scientific poster (individual work) 25%
Course costs for students:	No tuition fee Semester fee of ca 500 NOK Contribution to food on overnight stays (200 NOK/day, max 4 days)
Course costs for UNIS:	Ca. 440 000 NOK per year, excluding salary of UNIS staff

530   Electronic Appendix Supplementary Table B2: Key literature on Svalbard's geological evolution and main thematic topics.

Main theme	Selected key references
Overall introduction to Svalbard's geology	Worsley (2008), chapter 6-8 in Dallmann (2015)
CO$_2$ storage efforts in Svalbard	(Olaussen et al., 2019; Braathen et al., 2012; Senger et al., 2015b; Mørk, 2013)
Petroleum exploration	Nøttvedt et al. (1993), Senger et al. (2019)
Coal exploration and production	Senger et al. (2019), chapter 11 in Dallmann (2015), Harland and Anderson (1997)
Deep-time paleoclimate in Svalbard's geological record	Dypvik et al. (2011) - PETM Harding et al. (2011) - PETM Greenwood et al. (2010) - Eocene Arctic rainforest Uhl et al. (2007) - Fossil leaves in the Eocene of Spitsbergen Spielhagen and Tripati (2009) - Paleocene climate fluctuations Vickers et al. (2016) - Early Cretaceous climate Midtkandal et al. (2016) - Aptian global anoxia Hurum et al. (2016) - Barremian dinosaurs and climate Jelby et al. (2020) - Jr-Cr boundary and isotope signals Koevoets et al. (2016) - Jurassic isotope excursions Klausen et al. (2020) - Late Triassic delta and dinosaurs (Pott, 2012) - Late Triassic paleo-flora Paterson and Mangerud (2020) Mid-Late Triassic palynology and climate Wignall et al. (2016) - Early Triassic anoxia Zuchuat et al. (2020) - PT boundary Bond et al. (2015) - Mid Permian mass extinction Blomeier et al. (2011) - Permian change from warm/arid to cool climate

	Hanken and Nielsen (2013) - L.Carb.-E.Perm carbonate build-ups and climate variations
	Hüneke et al. (2001) - L.Carb.-E.Perm carbonates and climate variations
	Blomeier et al. (2009) - L.Carb. carbonates and Gondwana eustatic cycles
	Berry and Marshall (2015) - Devonian forest
	Fairchild et al. (2016) - Late Proterozoic glacial carbonate
	Knoll and Swett (1987) – Pre-Cambrian to Cambrian transition
	Hambrey (1982) - Late Precambrian tillites
	Bjørnerud (2010) - Kapp Lyell tillite (Neoproterozoic)
Paleogene	Dallmann (2015), chapter 6.10
	Helland-Hansen and Grundvåg (2021)
Cretaceous	Dallmann (2015), chapter 6.9
	Grundvåg et al. (2019)
Early Cretaceous magmatism	Senger et al. (2014)
Jurassic	Dallmann (2015), chapter 6.8
	Koevoets et al. (2019)
	Rismyhr et al. (2018)
Triassic	Dallmann (2015), chapter 6.7
	Anell et al. (2014)
	Lord et al. (2017)
Permian	Dallmann (2015), chapter 6.6
	Blomeier et al. (2013)
	Sorento et al. (2020)
	Matysik et al. (2018)
Carboniferous	Dallman (2015), chapter 6.5
	Smyrak-Sikora et al. (2019)
	Ahlborn and Stemmerik (2015)
Devonian	Dallmann (2015), chapter 6.4
Pre-Devonian	Dallmann (2015), chapters 6.2 and 6.3

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Figures and figure captions:

Figure 1: The digital geology revolution, as illustrated by the exponential growth in publications from 1990 to 2020 that include "photogrammetry" and "geology". Similarly, a marked increase is seen in publications including "geology" and "Svalbard". Data source: Google Scholar.
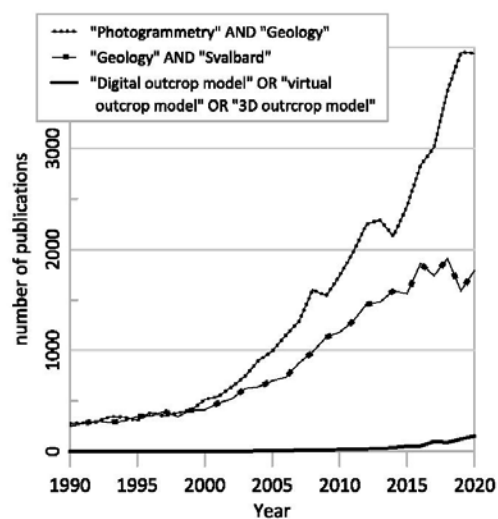
Figure 2: Overview of the Svalbox concept and its main elements. A) Screenshot from the UNIS-internal part of Svalbox, illustrating the correlation of multi-scale sedimentological logs from the Festningen outcrop integrated within the Petrel platform. B) Screenshot of the open-access part of Svalbox, with geological maps overlain with digital outcrop models, 360° imagery and geophysical data sets. Refer to Table 1 for details.
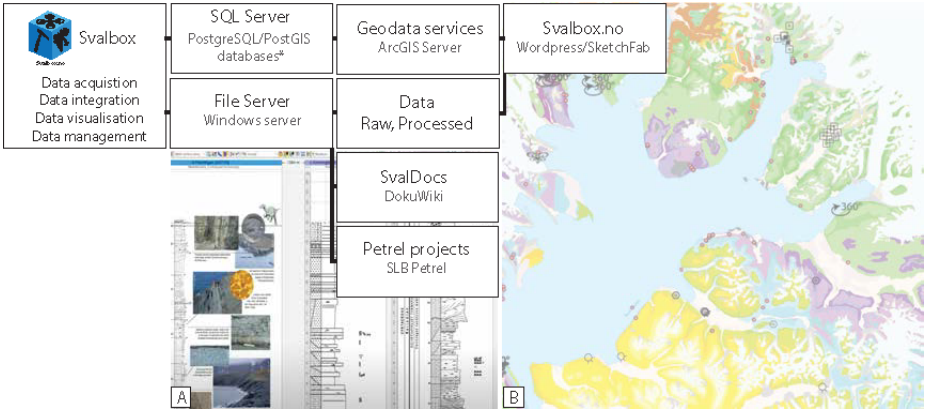
Figure 3: Location of Svalbard and the Billefjorden Trough, the main field area for the AG222 course. Winter and summer conditions of the same mountain, Løvehovden (see http://toposvalbard.npolar.no for exact location) are shown for comparison.

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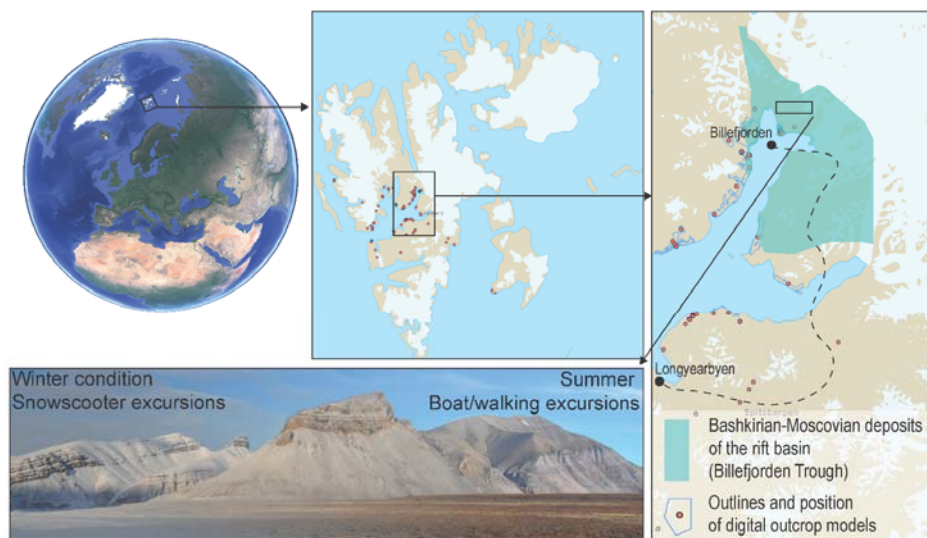
Figure 4: Extreme seasonal cycle, as exemplified by the amount of daylight hours, temperature, windspeed and snow depth in Adventdalen near Longyearbyen from 2017 to 2021 (meteorological source: https://klimaservicesenter.no/). The AG222 course and field periods are marked - these are characterized with maximum snow cover and lowest temperatures, and a rapid shift from no daylight to permanent daylight during the course period.

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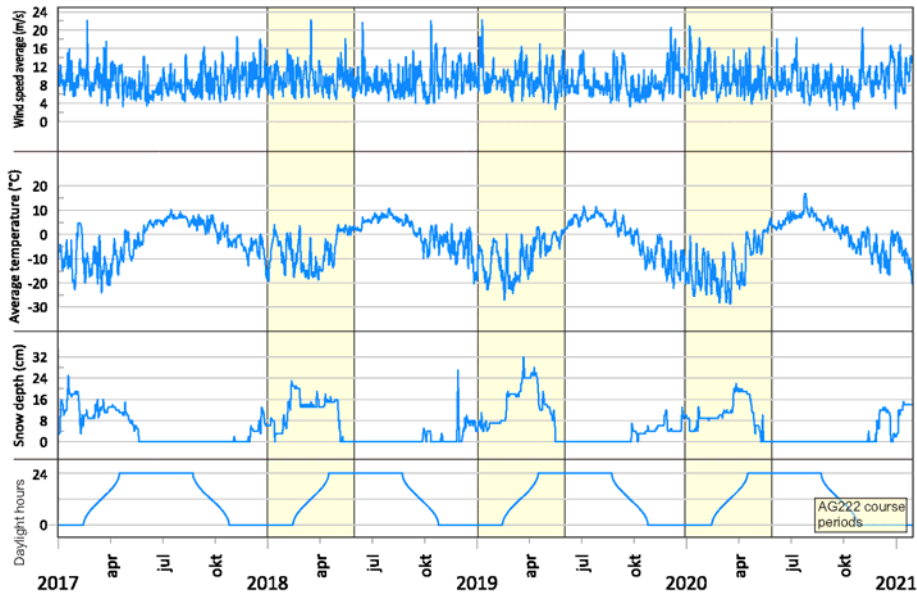
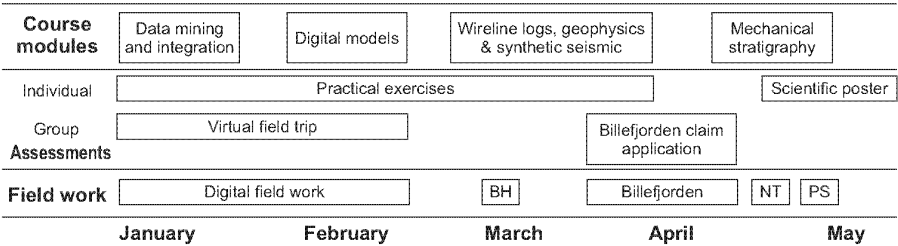
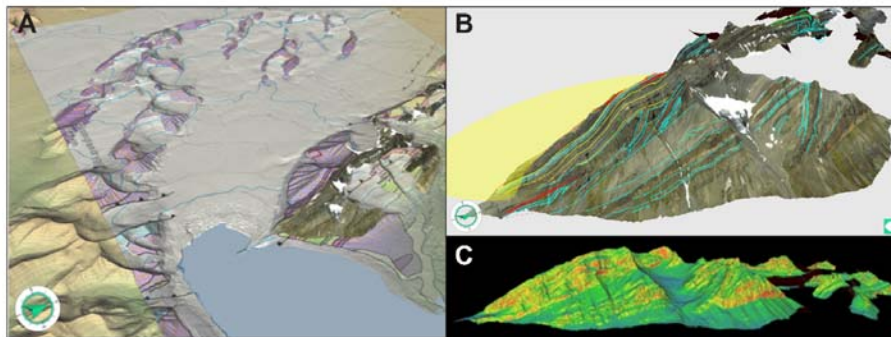
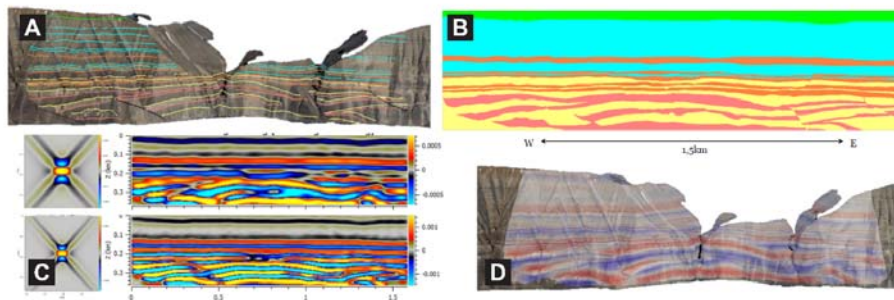

920   **Figure 5**: Overview of the central elements in the AG222 course, see Table 2 and 3 for details. The four course
modules are organised to build on each other, with skills learnt in the first half of the course highly relevant for
the second half. The two main graded group assessments are very intensive within a relatively short period,
while the graded individual assessment spans the entire semester giving student's flexibility to manage their
time. Field campaigns naturally follow the season, and each campaign has a clear learning objective. BH =
925   Botneheia day field trip, NT = near-town, PS = Polarsyssel (boat excursion on Isfjorden).

Course modules	Data mining and integration	Digital models	Wireline logs, geophysics & synthetic seismic	Mechanical stratigraphy
Individual	Practical exercises			Scientific poster
Group Assessments	Virtual field trip		Billefjorden claim application	
Field work	Digital field work	BH	Billefjorden	NT PS
	January	February	March	April	May

930   **Figure 6**: Screenshots from interpretation and integration of digital outcrop models, including textured DOM, slope calculation, elevation display and integration of the DOM with regional terrain models and geological maps. The illustrated example is from Mediumfjellet (https://v3geo.com/model/142; details on the structural geology in Larsen (2010) and Strand (2015). A) Regional digital elevation model and geological map (both courtesy of Norwegian Polar Institute) overlain by Mediumfjellet DOM. B) Close up of digital outcrop model,
935   with interpretations by Strand (2015). C) View of DOM from the south-east, with colour-coding representing the slope angle.

Field Code Changed

940 **Figure 7**: Examples from seismic modelling of the Kvalpynten digital outcrop model
(https://v3geo.com/model/90) conducted by the 2019 AG222 class on a ca. 2 km long part of the outcrop. A)
Interpretation of digital outcrop model using LIME. B) Assignment of elastic parameters to specific lithologies.
C) Seismic modelling under varying dominant frequencies using SeisRoX. D) Direct overlay of the seismic
model on the DOM.

Field Code Changed

945

Figure 8: Examples from the Billefjorden license claim assignment, conducted by the 2019 AG222 class. A)
Top Reservoir structure contour map with fault zones and the area to be fictively claimed (red rectangle). B)
Well prognosis, illustrating key petroleum system elements like source and reservoir rocks. C) East-west cross
section across the proposed drill site.

955 **Figure 9**: Applications of DOMs for concrete usage in teaching.

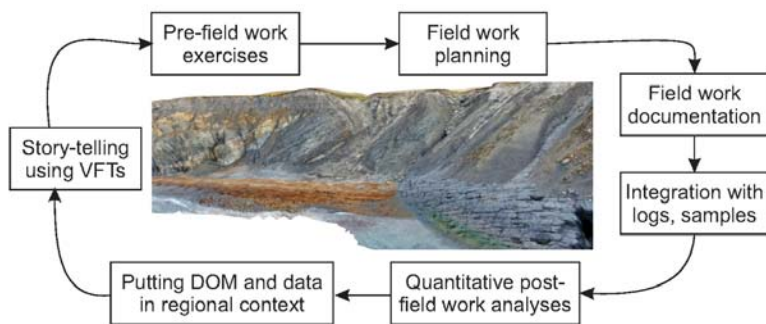



Figure 10: Schematic diagram of the synergies between the AG222 course (and other UNIS courses and

 research activities) and the Svalbox portal.

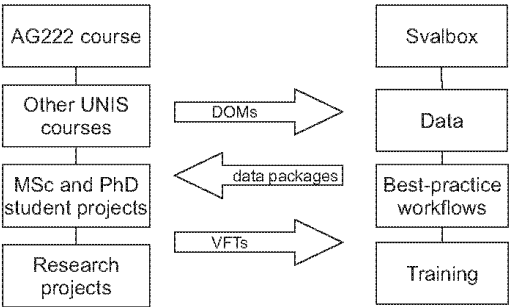



Figure 11: Consequences of the Covid-19 pandemic on the AG222 assessment related to the license claim
application.