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Using digital outcrops to make the high Arctic more accessible through the Svalbox database

Kim Senger[a], Peter Betlem[a,g], Thomas Birchall[a,g], Simon J. Buckley[b], Bernard Coakley[c], Christian H. Eide[d], Peter P. Flaig[e], Melanie Forien[f], Olivier Galland[g], Luiz Gonzaga, Jr.[h], Maria Jensen[a], Tobias Kurz[i], Isabelle Lecomte[d], Karen Mair[g], Rie Hjørnegaard Malm[g], Mark Mulrooney[g], Nicole Naumann[b], Ivar Nordmo[j], Nils Nolde[k], Kei Ogata[l,m], Ole Rabbel[g], Niklas W. Schaaf[a], and Aleksandra Smyrak-Sikora[a,d]

[a]Department of Arctic Geology, The University Centre in Svalbard, Longyearbyen, Norway; [b]NORCE Norwegian Research Centre AS, Bergen, Norway; [c]Geophysical Institute, University of Alaska, Fairbanks, AK, USA; [d]Department of Earth Science, University of Bergen, Bergen, Norway; [e]Jackson School of Geosciences, Bureau of Economic Geology, University of Texas at Austin, Austin, Texas, USA; [f]Department of Geosciences, University of Tromsø - The Arctic University of Norway, Tromsø, Norway; [g]Department of Geosciences, University of Oslo, Blindern, Oslo, Norway; [h]Advanced Visualization Laboratory, University of Vale do Rio dos Sinos, São Leopoldo, RS, Brazil; [i]Geological Survey of Norway, Trondheim, Norway; [j]Department of Pedagogics, University of Bergen, Bergen, Norway; [k]Geophox, Berlin, Germany; [l]Faculty of Earth and Life Sciences, Geology and Geochemistry Cluster, VU Amsterdam, Amsterdam, Netherlands; [m]Department of Earth Sciences, Environment and Resources, University of Naples Federico II, Naples, Campania, Italy

ABSTRACT

The high Arctic is a remote place, where geoscientific research and teaching require expensive and logistically demanding expeditions to make use of the short field seasons. The absence of vegetation facilitates the use of modern photogrammetric techniques for the cost-effective generation of high-resolution digital outcrop models (DOMs). These georeferenced models can be used in pre-fieldwork activities to help prepare for traditional geological fieldwork, during fieldwork to record observations, and post-fieldwork to conduct quantitative geological analyses. Analyses of DOMs range in scale from mm-cm (e.g., size and spacing of dinosaur footprints), to hundreds of meters (e.g., seismic modeling of outcrops and outcrop-well-seismic correlations) and can advance research objectives. This integration is strengthened if key geoscientific data, like geological and topographical maps, subsurface profiles, borehole data, remote sensing data, geophysical data and DOMs can be integrated through a common database, such as the Svalbox database that we present in this commentary. Svalbox geographically targets the Svalbard archipelago, where fieldwork is challenging due to the harsh polar environment, risk of polar bear encounters and demanding transport to the field area. The University Centre in Svalbard nonetheless relies on utilizing the natural Svalbard environment for its field-based education, and now makes use of Svalbox to make geological fieldwork more efficient and post-fieldwork analyses more quantitative. Experience and usage of such tools in geoscientific education, particularly in the polar regions, is not well documented. Therefore, we share experiences on both developing and optimizing Svalbox, and on student and lecturer usage. Svalbox includes a web-based interface through which DOMs are shared and displayed together with relevant public-domain geoscientific data sets. Svalbox also serves as a platform to share student and teacher experiences on the entire DOM workflow, from acquisition to data distribution. For the Svalbox users questioned by the project group, DOMs were found to provide many benefits, including quantitative analyses, extended field season, appreciation of scale and data sharing that significantly outweigh present-day challenges, such as the need for expensive hardware and lack of easily accessible interpretation software, the latter being surmountable within the near-term.

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Introduction

Field excursions are a fundamental aspect of educating geoscientists (Kastens et al., 2009; Mogk & Goodwin, 2012), allowing students and professionals alike to observe geological features to piece together the geologic evolution of an outcrop or area. Teaching and learning in the field are one of the four pillars of geology, besides temporal thinking, spatial thinking and considering the Earth as a complex system (Kastens et al. 2009). Field learning provides authentic experiences of geological observation and analysis, such as understanding scale and filtering complex systems into their critical and less important elements. Pre-fieldwork activities familiarize students with methodology and possibilities to practice skills in a controlled environment, help students gain more knowledge while in the field, and help students to engage in field learning objectives at a more advanced level. Field teaching takes

CONTACT Kim Senger kim.senger@unis.no Department of Arctic Geology, The University Centre in Svalbard, PO Box 156, 9171 Longyearbyen, Norway.
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place outside per definition, where weather, comfort, safety and the introduction to a new environment create a challenging learning environment.

In recent years new technologies have provided novel opportunities to study processes and to survey large areas (Bemis et al., 2014; Nesbit et al., 2018). As a consequence, geoscientists have, to some extent, abandoned the field and based their research on results from the laboratory or computer models (Turner, 2000). Students in higher education geology must, however, learn to record observations from various sources, apply critical reasoning, synthesize the data, and construct interpretations in authentic field-settings (Dodick et al., 2009; Frodeman, 1995). Field excursions enable the observation and interpretation of (past and present) geological processes by examining the rocks and their associations. Student spatial and temporal thinking can be addressed directly in the field by experiencing real-scale geological outcrops, correlating geology across several outcrops and on a basin-scale. Fieldwork can thus support student learning in difficult threshold concepts such as spatial understanding (Kastens & Ishikawa, 2006), and the concepts of scale (King, 2008) and deep time (Kortz & Murray, 2009). These threshold concepts can also be trained with various applications and software targeting geoscience students, which challenges the position of fieldwork in the curriculum.

The virtual pre-field activities do not replace the experience of size, scale and the physical character of materials as obtained in the field, but can serve as a high-quality addition for distance education, shared course content between institutions, and as a way of providing inclusion and access to field knowledge for underrepresented groups in geology. Instead of leaving the field behind, we argue that it is more beneficial to integrate digital technologies with fieldwork (Table 1). In doing so, the students have the opportunity to work with multiple scales and 3 D visualizations of data from the field while in class, before and after fieldwork, which adds to the learning potential both in the field and in class.

In the Norwegian archipelago of Svalbard (74-80°N, 15-35°E) and elsewhere in the high Arctic fieldwork is hampered by the short field season, site-specific hazards (e.g., polar bears, rock falls, glacial landscape, harsh weather conditions), significant cost of field logistics (€3000/day is an average budget for a 20 student BSc class on a scooter excursion) and challenges such as traveling to and from the field area and acquiring relevant permits. With its nearly continuous Devonian-Neogene stratigraphic record (Dallmann et al., 1999; Worsley, 2008), Svalbard has attracted geologists for centuries. Geological and geophysical data have been acquired over time for different purposes, e.g., for coal and petroleum exploration (Senger et al., 2019) and research drilling (Olaussen et al., 2019), that provide important insights into the subsurface.

The University Centre in Svalbard (UNIS) is the world's northernmost higher education institution and offers undergraduate and graduate education in Svalbard. To utilize the natural laboratory of Svalbard to its full potential, UNIS' Arctic Geology curriculum relies on maximizing the use of the two main field seasons: the late winter/spring and the short summer (Figure 1A; Senger & Nordmo, 2020). The long period of midnight sun partly compensates for the brevity of the field seasons, though conditions are typically cold even in summer, making extensive work periods at outcrops challenging. It is, thus, imperative to make efficient use of field days in Svalbard. This requires preparation using available data and studies from the respective field area, preferably including preexisting digital outcrop models (DOMs). Extensive DOM acquisition can be fine-tuned to avoid repetition and lower the environmental and economic costs of high Arctic fieldwork. DOMs may be acquired either through ground-, UAV- or helicopter-based lidar scanning (Buckley et al., 2008; Hodgetts, 2013; Rittersbacher et al., 2013), or through structure-from-motion photogrammetry (Bemis et al., 2014; Smith et al., 2016; Westoby et al., 2012). These can be augmented with ultra-high-resolution 2 D imagery of outcrops using GigaPan photo-mosaics (e.g., Flaig et al., 2019; Guerin et al., 2015; van der Kolk et al., 2015). During outcrop investigations, complementary data and observations beyond the resolution of the DOM are usually collected, including physical samples, structural measurements and sedimentary logs. The digital field notebook, presented by Senger and Nordmo (2020), makes use of off-the-shelf applications running on field-proofed tablets to further increase the effectiveness of high Arctic fieldwork and facilitate the inclusion of digital field data in Svalbox.

Effective preparation for fieldwork can be accomplished with virtual field trips (Arrowsmith et al., 2005; Dolphin et al., 2019; Jacobson et al., 2009; McCaffrey et al., 2010; Mead et al., 2019; Senger, 2019a; Stott & Nuttall, 2010) by utilizing DOMs, 360° imagery and associated data (e.g., Svalbox; Senger, 2019b). This digital experience has been successfully used in education, particularly when associated with e-learning modules (Hesthammer, 2003) or geosimulators such as the software SvalSIM developed by the petroleum industry (Saether et al., 2004). Both virtual field trips and geosimulators allow students to visit the field site

Table 1. Overview of the different tools used at different stages within courses at UNIS.

Phase	Requirements	Purpose	Tools presently used
Pre-course	No hardware requirements, easy access with "standard" PCs	Pre-course assignments, familiriazation with outcrops	3D pdf, web-viewers
Pre-fieldwork	Detailed virtual outcrop interaction	Fieldwork planning, some interpretation	LIME, Petrel, Move, Google Earth
During fieldwork	Visualization of virtual outcrops in the field	Seeing the "big" picture, maintaining overview	3D pdf apps, FieldMove
Post-fieldwork	Detailed interpretation and processing of new data	Detailed interpretation, processing and integration	LIME, Metashape, Petrel
Post-course	No hardware requirements, easy access with "standard" PCs	Outreach to general public	3D pdf, web-viewers

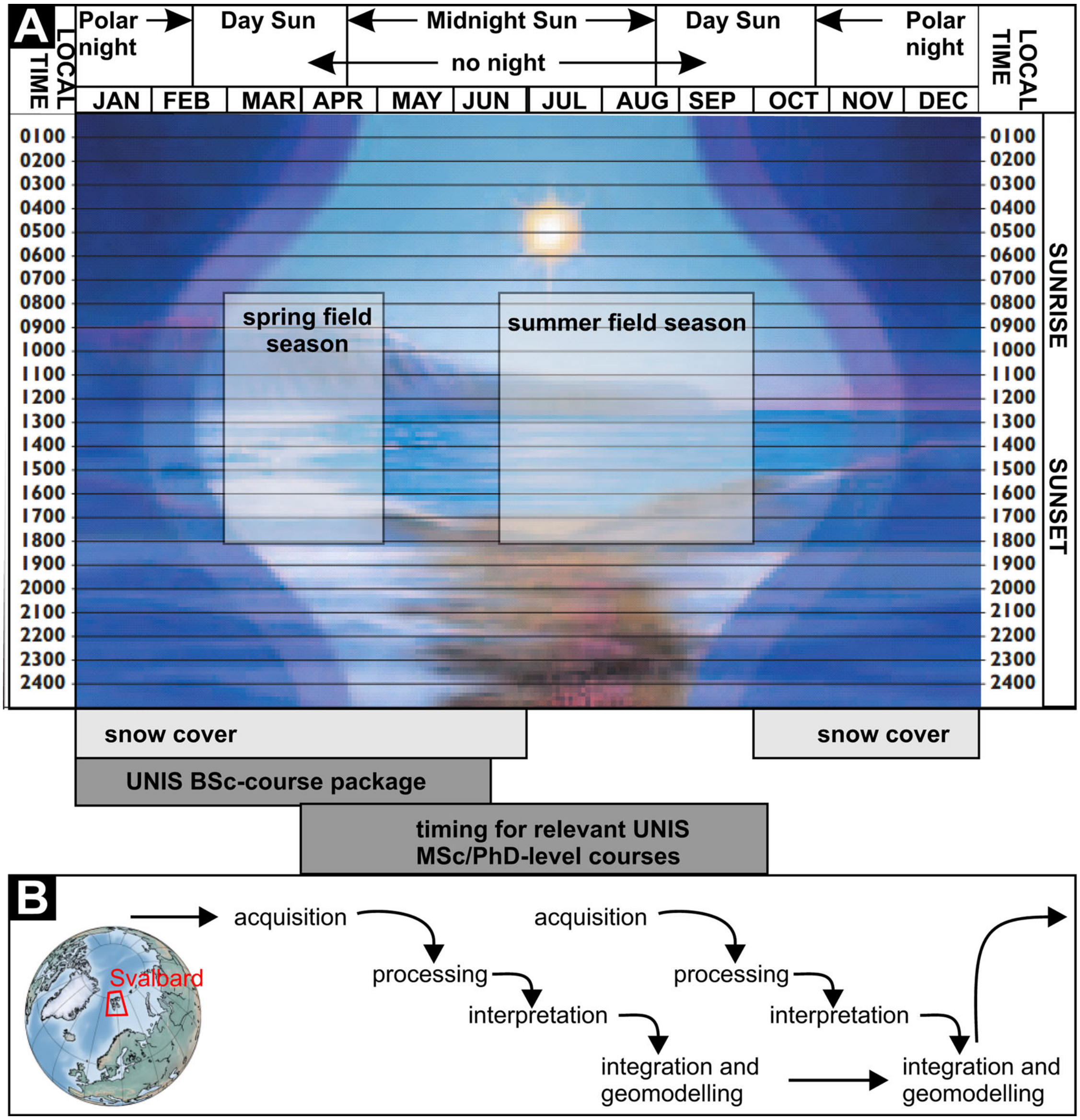

Figure 1. Seasonal control on field activities in Svalbard. A) Sun diagram for Longyearbyen, overlain with the main field seasons and timing of courses at the University Centre in Svalbard. Sun diagram provided by Longyearbyen Community Council. B) Annual cycle of acquiring photographs for virtual outcrop model processing, interpretation and integration. The inset map shows the position of Svalbard between continental Norway and the North Pole.

virtually. Google Earth (Bailey et al., 2012 and references therein), for instance, provides a user-friendly platform for conducting digital geological excursions but is unfortunately hampered by very poor base map imagery in Svalbard. Gonzaga et al. (2018) and Hossa et al. (2019) demonstrate the Multi-Outcrop Sharing and Interpretation System (MOSIS) that allows educators and researchers to visit DOMs in a virtual reality environment and conduct quantitative geological measurements. MOSIS Lab is an x-reality virtual and immersive laboratory where users can visualize and manipulate digital 3 D models, texts, audios, and other kinds of media from different sources. The system offers a non-disruptive immersive environment allowing users to correlate data with realistic visual feedback and is promising in augmented and virtual fieldwork. Such quantitative measurements of digital outcrops independent of seasons and other access challenges are a real advantage of virtual reality fieldwork.

In this commentary we present a geo-referenced database, Svalbox, that provides an opportunity to visit real field sites as part of the pre-fieldwork activities. These are framed around virtual field trips that integrate many data sets including DOMs. The Svalbox portal facilitates the bridging of traditional field work with the classroom setting by providing the students access to a range of relevant data sets that enables them to place their outcrop-scale observations in a regional perspective. We share our experience of utilizing digital tools in undergraduate and graduate geological education at UNIS through the Svalbox concept. Firstly, we present the Svalbox concept and the courses that it is used in. We then outline the Svalbox database, an interactive 3 D collection of a wide range of georeferenced data sets including DOMs. Further we present our workflow of acquiring photos at a range of scales, using boats, hiking or drones to generate DOMs. We also illustrate the map-based interface of the Svalbox website, where acquired DOMs are shared

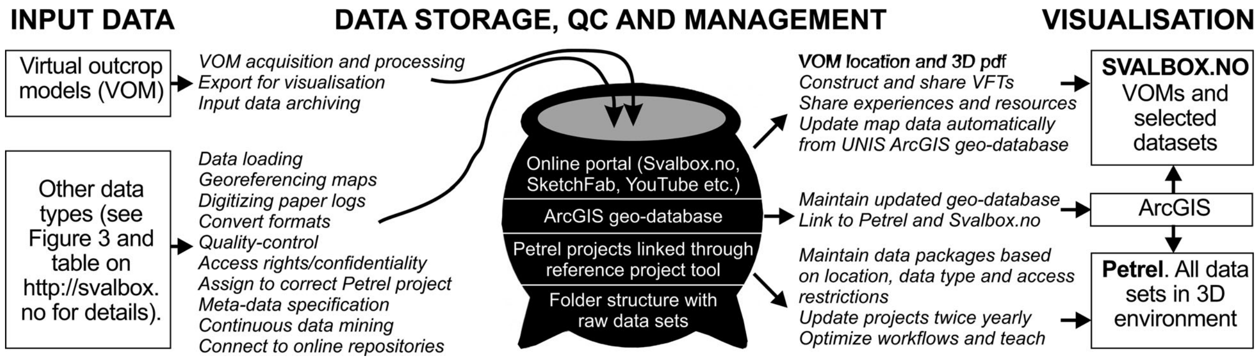

Figure 2. Flow chart illustrating the different components and workflows (in italics) within Svalbox.

with the general public. In addition, we present qualitative experiences on the process of developing and using Svalbox from the perspective of both teachers and students. Finally, we document "off-the-shelf" software tools that we use in education, both at the university (on high-end computers) and in the field (on tablets; Senger & Nordmo, 2020).

What is Svalbox, and how is it used at UNIS?

The key objective of the Svalbox database is to integrate multiple data sets within an easy-to-use interface for education and research. Svalbox is geographically restricted to the Svalbard archipelago and its surroundings (Senger, 2019b), but the concept is easily applicable elsewhere. Figure 2 illustrates the different components of Svalbox as well as the key workflows, while regularly updated tables on the Svalbox website including data sets and online resources summarize the various data types and sets incorporated at present. Figure 3 illustrates both the range and regional spatial coverage of the various data types currently available within Svalbox. Svalbox aims to fulfill two key objectives: 1) follow a multi-scale and multi-data approach with an "all-can-be-integrated" approach, and, 2) provide published maps, profiles and sedimentary logs in publications and books in an interactive and geo-referenced 3 D environment (i.e., an interactive reading list).

Svalbox's online interface (https://svalbox.no) is sourced directly from an internal ArcGIS server with Microsoft SQL backend at UNIS. DOMs and seismic navigation files are semi-automatically incorporated into the ArcGIS database through a Python application programming interface (API) and scripting. The base satellite and topographic maps, as well as the geological map layer, are streamed to the web interface from the Norwegian Polar Institute's geodata portal (NPI, 2019).

Since 2016 we have been continuously implementing the digital tools used as part of the Svalbox concept, including active use of DOMs and digital field notebooks (Senger & Nordmo, 2020). We have implemented Svalbox in two full-semester undergraduate courses at UNIS (AG222 and AG209, 15ECTS each), as well as in three MSc/PhD-level courses (AG322, AG334, AG336; 10ECTS each; see http://unis.no for details; Table 2). All the courses at UNIS are constructed with extensive fieldwork elements. It is important that students have solid base-level skills, a familiarity with the relevant methodologies, and understand different ways of displaying data and background knowledge.

The Svalbox data repository provides a foundation for access to real data and a digital basis for the integration of numerous data types. Access to real data sets allows students to become familiar with the data behind publications, practice the description and understanding of different types of data, carry out exercises analyzing data sets and start to identify and select data sets relevant to solve authentic problems. DOMs provide a tool for students to practice observation and descriptive skills in the classroom, make measurements and do plots of observations, and experiment with comparing their own observations with existing data sets. These models also provide an integrative framework for more traditional geologic samples (e.g., hand samples, thin sections and drill cores) that give spatial context to the isolated pieces of outcrop that geology lab education has employed.

AG222 ("Integrated Geological Methods: from outcrop to geomodel") was first run in 2018, and runs annually from mid-January to late May. This period is, as noted above (Figure 1), challenging with respect to accessing outcrops and conducting extensive fieldwork. As part of the AG222 course the students are assigned to groups of four and participate in three main activities involving Svalbox, namely: i) In the classroom before the fieldwork, students develop and present a virtual field trip to a given locality, ii) the fieldwork component covers a 4-day excursion to the Billefjorden Trough, during which the students participate in collecting data and later submit a (fictive) "license claim" application built on data gathered in the field and integrated from other sources, and iii) final poster presentation highlighting the use of one of the methods learned during the course (typically sedimentological logging, structural logging, digital outcrop modeling or seismic modeling). The AG222 students use Svalbox to access data sets in all three steps, from the virtual field trip, to learning the various methods, in particular DOM processing and interpretation.

AG222 runs in parallel with the complementary course AG209 ("The Tectonic and Sedimentary History of Svalbard"), where the same students are exposed to different parts of Svalbard geology through excursions and individual research projects. The focus of AG209 is on the geological evolution of Svalbard. The AG209 students use Svalbox to prepare for their regional fieldwork, and access data sets for

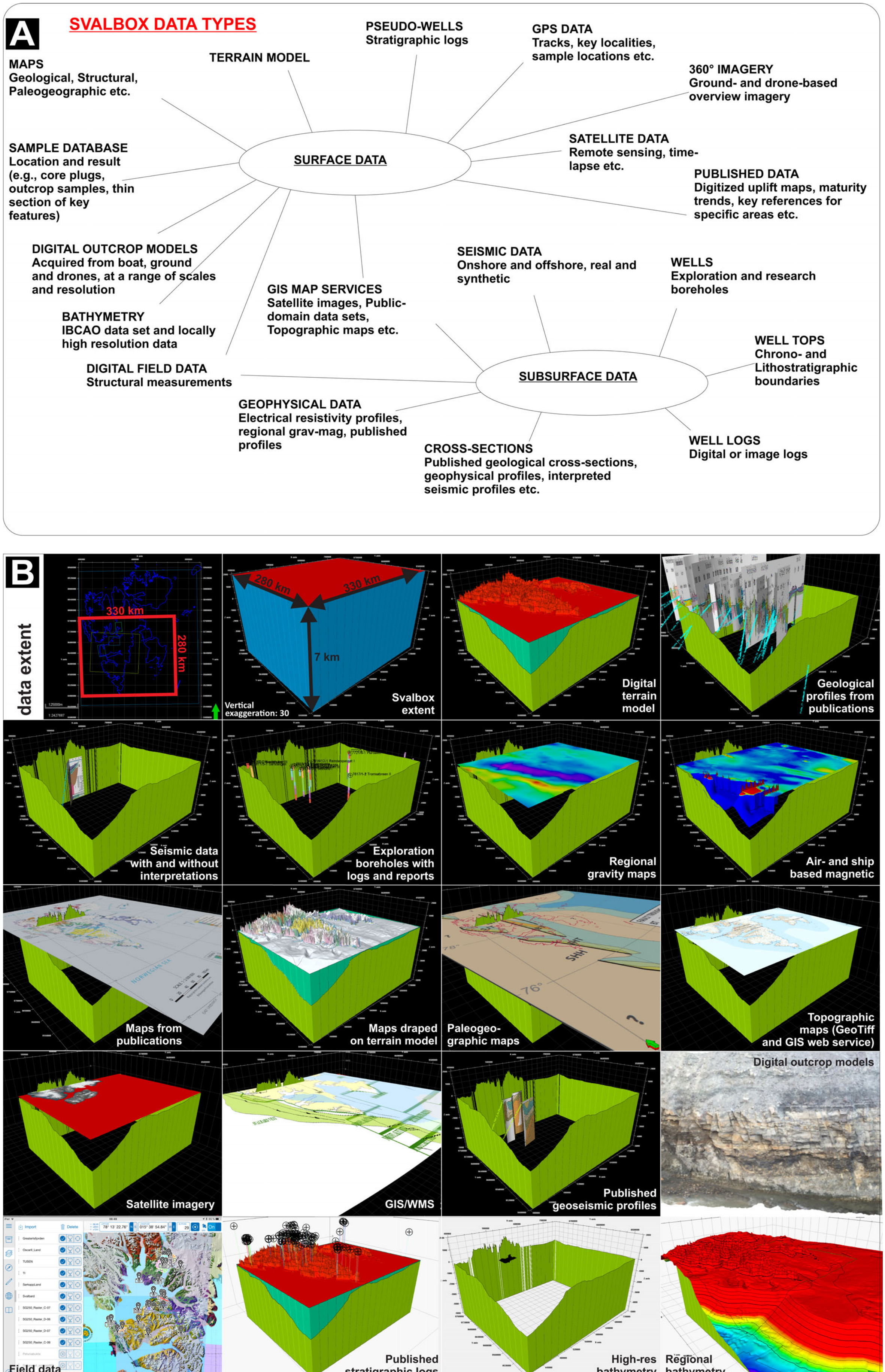

Figure 3. Synthesis of data sets incorporated in the Svalbox database (A) and their spatial distribution (B) within the 3D Svalbox database, screenshots from Petrel.

their individual research projects as part of the course (Table 2).

We have also implemented the Svalbox concept in numerous graduate-level courses at UNIS, though often in a condensed 2-4 hour introduction session. The brief introduction allows the students to gain an overview of the available data sets, and access these through the UNIS internal and web-based Svalbox portals. In addition, the best-practice workflows developed by the Svalbox team are shared with the students. MSc and PhD students at UNIS are active Svalbox users and also contribute with new data sets (Table 2).

As part of this study, we have acquired qualitative and quantitative data to characterize the experiences that different user groups (primarily students, teachers and petroleum industry collaborators) have with DOMs using an anonymous online questionnaire implemented with Google Forms

Table 2. Summary of the courses where Svalbox is actively used, with emphasis on the full-semester Bachelor course package AG222 and AG209.

Course code and name	Selected learning outcomes and goals	Teaching interventions	Technological tools used
AG222 - Integrated geological methods: from outcrop to geomodel (15ECTS)	Develop a basic understanding of geological field mapping techniques (e.g., stratigraphic and structural mapping at outcrop and core scale)	Field excursions to representative outcrops of different formations	Digital field notebooks (in the field) and Svalbox portal for preparing excursion
	Develop a basic understanding of geophysical data interpretation techniques (e.g., seismic, electric methods, wireline log interpretation)	Introduction lecture and group exercise on various geophysical methods	Svalbox portal and Petrel data package for data access, integration and interpretation
	Actively use modern tools (e.g., photogrammetry to construct digital outcrops, industry-standard software) to link geology and geophysics together to construct a realistic geo-model of a study area	Dedicated module on DOM acquisition, processing and interpretation	Acquisition systems (DSLR cameras, drones), processing software and Svalbox portal for sharing DOMs
AG209 - The Tectonic and Sedimentary History of Svalbard (15ECTS)	Be able to do sedimentological logging, description and analysis of relevant formations both in the field and in cores.	Field excursions to representative outcrops and available core material of different formations	Sharing of digital drill core and outcrop models with students. Geo-referenced note and observation taking with digital field notebooks.
	Be able to describe large-scale geological structures such as folds and faults in the field and draw geological sketches and profiles.	Practice sketching using photographs and 3D models prior to field excursion	Overview photographs, DOMs from different perspectives, drone overview videos
	Be able to recognize common fossils from the geological record in Svalbard.	Lectures and exercises on evolution of life in Svalbard rock record	3D models of hand samples and fossils in field
	Be able to do simple analyses of seismic sections and understand how seismic data corresponds to rock types visited in the field.	Exercises and term projects using seismic data	Integration of well logs and seismic data to correlate outcrops , provision of data through Svalbox
	Be able to carry out small independent research projects on the geology of Svalbard and present findings to others.	Provision of data and topics for term projects to deepen knowledge discussed in class	Provision of all required data through Svalbox portal
Other MSc/PhD-level courses (e.g., AG322, AG334, AG336; all 10ECTS each see https://www.unis.no/studies/geology/ for details)	Be able to use different types of geological data (structural, sedimentological) to reconstruct the architecture and the general tectonic and depositional history of a rift basin.	Class field excursion and extensive group field work to collect own observations and field data	Provision of all required data through Svalbox portal, digital field data collection using digital field notebook, drones etc.
	Strengthened their ability to think across disciplines and to implement cross-disciplinary concepts in a team-based workflow.	Assign multi-disciplinary groups and assign relevant field-based tasks	Data provision in Svalbox portal, integration of geological and geophysical data sets
	Have broad knowledge of concepts of fold-thrust belts and their link to sedimentary systems of foreland basins.	Organize multi-day field excursion across entire width of foreland basin and orogenic belt	Digital field data collection across entire basin, provision of examples of DOMs from different parts (both visited and not visited)
	Hands-on experience of the workflow on modern works stations in the industry, combining data from wire line logs, core data and onshore/offshore seismic.	Assign relevant and authentic exercises	Integration of data in Svalbox portal
MSc and PhD theses	Conduct independent research projects, incorporating own observations in the context of the current state-of-the-art	Development of realistic thesis plan, ongoing supervision	Svalbox portal as a digital data package provided at start. Svalbox as a means to share own results (e.g. DOMs) with scientific community following project completion.

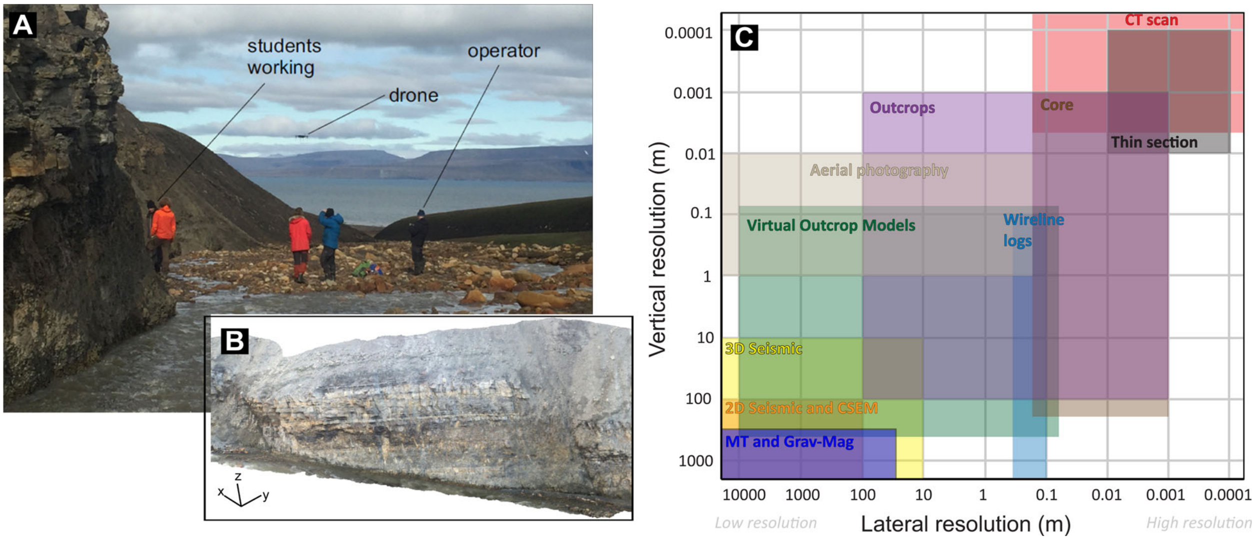

Figure 4. Outcrops and geoscientific data types at different scales. A) B) Digital outcrop model (DOM) of part of the Longyearbyen CO2 lab reservoir, processed from 75 images taken using an iPhone 6 smartphone. The DOM has a 0.24 cm pixel resolution, covers an area of 40*8 m, comprises 5.4 million points triangulated across 120,000 faces. DOMs are included in the supplementary material in an interactive 3D pdf format. C) Summary of data sets typically used in subsurface characterization, as a function of the vertical and lateral resolution. Outcrop studies on Svalbard are designed to complement existing subsurface data within the indicated spatial ranges. Figure modified from Matt Hill (Agile Geoscience). CT = Computed tomography; CSEM = controlled source electromagnetic; MT = Magnetotelluric.

(n = 36). The survey was sent to the wide network of the international project team that spans across disciplines (structural and sedimentary geology, geophysics, volcanology, geomatics etc.) and roles (from BSc students to Professors, and petroleum industry professionals). To compare experiences of different student groups, we have categorized the respondents into three categories, namely students (BSc and MSc, n = 14), academics (PhD students, PostDocs, Researchers, Associate Professors and Professors, n = 15) and industry professionals (n = 7). Since we are in the development and optimization stage of Svalbox and related tools, we have not yet attempted to quantify the effects that the implementation of the digital tools will have on student learning.

Digital outcrop models: Applications, processing, interpretation and user experiences

The foundations of the Svalbox portal are the digital outcrop models and their integration with complementary surface and subsurface data sets.

DOM: Applications

Geoscientists utilize various data sets including seismic surveys, borehole data, aerial photography, traditional outcrop geology and micro-structural observations. These data sets span a wide range of scales, the vertical and horizontal resolutions of which are plotted in Figure 4C. The gap in data of intermediate resolutions, particularly between seismic data and well data scales, requires inferences or estimates, which can be a significant source of error. Traditionally, outcrop geology has played an important role owing to the wide variation of spatial resolution it can encapsulate, in sharp contrast to well data, which provides mm- to m-scale vertical resolution (wireline data and core material), but is laterally very limited. Aerial photographs can accommodate some of these intermediate scales, but they are essentially 2 D qualitative data without vertical resolution. On the finer end of the spectrum, microscopic lab-based analyses are usually required for discerning rock properties such as porosity and permeability, as well as fracture characterization.

DOMs have traditionally held quantitative information on reservoir architecture for the petroleum industry (Enge et al., 2007; Hodgetts, 2013; Pringle et al., 2006). Development of DOMs previously required lidar-scanning (Buckley et al., 2008; Howell et al., 2014; Rittersbacher et al., 2013). In recent years, photogrammetric processing provides an alternative means to generate DOMs at much lower cost than lidar scanning (Bemis et al., 2014; Nesbit et al., 2018; Smith et al., 2016; Westoby et al., 2012). Furthermore, increased availability of affordable drones provides the field geologist unprecedented means of effectively capturing DOMs at a range of scales (Cawood et al., 2017; Galland et al., 2019; Rabbel et al., 2018). In particular, such drone-based DOMs make inaccessible cliffs, which commonly offer the best exposures, safely available. Regardless of how the DOMs are generated, quantitative analysis relies on access to suitable visualization and interpretation software (Buckley et al., 2019; Hodgetts, 2013). DOMs are routinely used in fracture characterization (Casini et al., 2016; Larssen, 2018), sedimentary body quantification (Chesley et al., 2017; Howell et al., 2014; and references therein), mapping of igneous bodies (Galland et al., 2019), performing tempo-spatial analysis of growth faults and associated basin fills (Ogata et al., 2018; Smyrak-Sikora et al., 2019) or as input for seismic modeling (Anell et al., 2016; Eide et al., 2018; Rabbel et al., 2018). In recent years, DOMs have also been used as a framework to support education and geological training (Senger et al., 2018). A key advantage is the scalability of DOMs, as they can be constructed from hand-sample to km-scale outcrops (Figure 4; Betlem et al., 2020;

Rabbel et al., 2018). Furthermore, the ability to "re-visit" the outcrop digitally even outside the short field season, is beneficial particularly in remote areas with a short field season like Svalbard. Such a virtual visit may also be applicable when assessing the fieldwork component of the courses. The same benefits apply for other polar and non-polar field areas with long access distances, such as the El Manzano outcrop in remote parts of Argentina (Rabbel et al., 2018) or the outcrops of Jameson Land in east Greenland (Eide et al., 2018). Figure 5 summarizes what the survey respondents use DOMs for, with sedimentological (83% of respondents) and structural (64%) characterization dominating together with the documentation of the field area (67%). The relatively high use of the specialized technique of seismic modeling (56%) is likely due to the active use of this technique by the project team in both research and teaching, including in AG222.

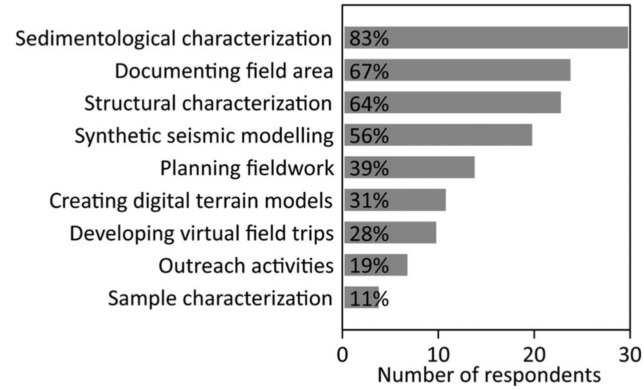

Figure 5. Summary of what DOMs are used for by the survey respondents (n = 36). Note that several options could be indicated by the survey participants.

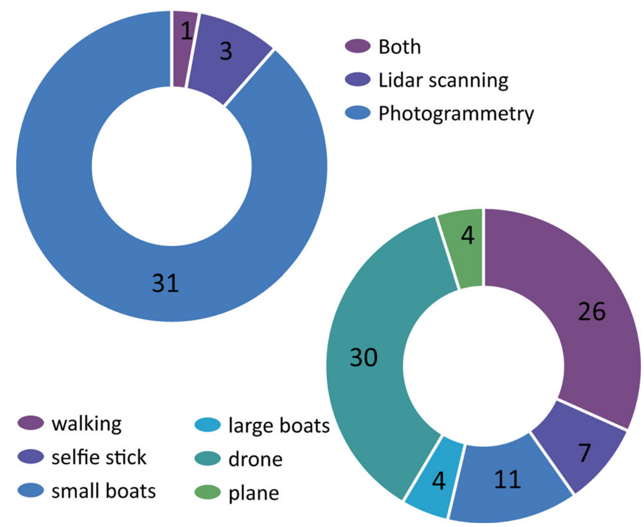

Figure 6. Acquisition techniques used by the survey respondents. Several options could be indicated for the photogrammetry acquisition techniques.

DOM: Acquisition

We utilize ground-, boat- and air-borne photo acquisition platforms to generate the majority of the DOMs presented in Svalbox (Figure 4; Figure 6). Unmanned aerial vehicles (UAVs, i.e. drones; Figure 4A) with high-resolution cameras are flown alongside or above outcrop belts in an overlapping grid pattern (Chesley et al., 2017). Global navigation satellite system (GNSS) capabilities built into the UAV provide information on the location of the aircraft during the acquisition of each image. This information is critical when processing the imagery into geo-referenced 3 D point clouds. Cheap and easy acquisition of images for DOMs can be made with GPS-enabled digital single-lens reflex (DSLR) cameras or even mobile phones, making the method available and affordable for students.

Although qualitative rather than quantitative, GigaPan technology, which employs a tripod-mounted ground-based robotic panhead with a high-resolution DSLR camera and long focal length lens, produces ultra-high-resolution outcrop images that can be used to complement the 3 D DOMs. Hundreds of overlapping images are captured in a preprogramed grid pattern and stitched together into large photo-mosaics that provide details not typically captured in drone photogrammetry. Examining GigaPan imagery alongside DOMs can provide highly valuable additional detail during the interpretation phase (e.g., Flaig et al., 2019; van der Kolk et al., 2015).

In Svalbard and other polar areas, additional acquisition challenges arise from the remote and harsh environmental setting. Here, the glaciated mountainous landscapes, quickly changing weather conditions, and the chance of polar bear encounters, pose challenges to surveying campaigns. UAV-based acquisition is further complicated by low temperatures, magnetic interference, and frequent loss of GPS signal. The actual surveying is predominantly governed by accessibility to the field site and exposure of the outcrop. Ground-, UAV- and boat-based acquisitions are often combined to maximize outcrop exposure (i.e., accessibility) at different scales and to minimize risk (Figure 4C). Acquisition is, indeed, only possible during a brief period in which access (e.g., by snowmobile, boat, on foot) is feasible and the outcrop is exposed (e.g., snow has melted).

DOM: Processing and interpretation

Following acquisition of geo-referenced photographs DOMs are generated using photogrammetry. Models generated by our study (Appendix I, and https://svalbox.no) were processed using Agisoft's Metashape Professional Edition; however, multiple freeware software packages with similar functionality are also available. The structure-from-motion processing workflow is summarized in Figure 7A and in numerous publications (Carrivick et al., 2016; Fonstad et al., 2013; James et al., 2019; James & Robson, 2012; Nesbit et al., 2018; Smith et al., 2016; Westoby et al., 2012). Sparse and dense point clouds are generated from similar matched features in multiple images. A 3 D triangulated mesh depicting outcrop geometry is produced, upon which the original photograph textures can be draped. Additional visual attributes, e.g., surface directionality (including strike and dip; Figure 7B), can also be draped on the DOM.

Students and researchers can export DOMs from structure-from-motion processing software to a variety of formats

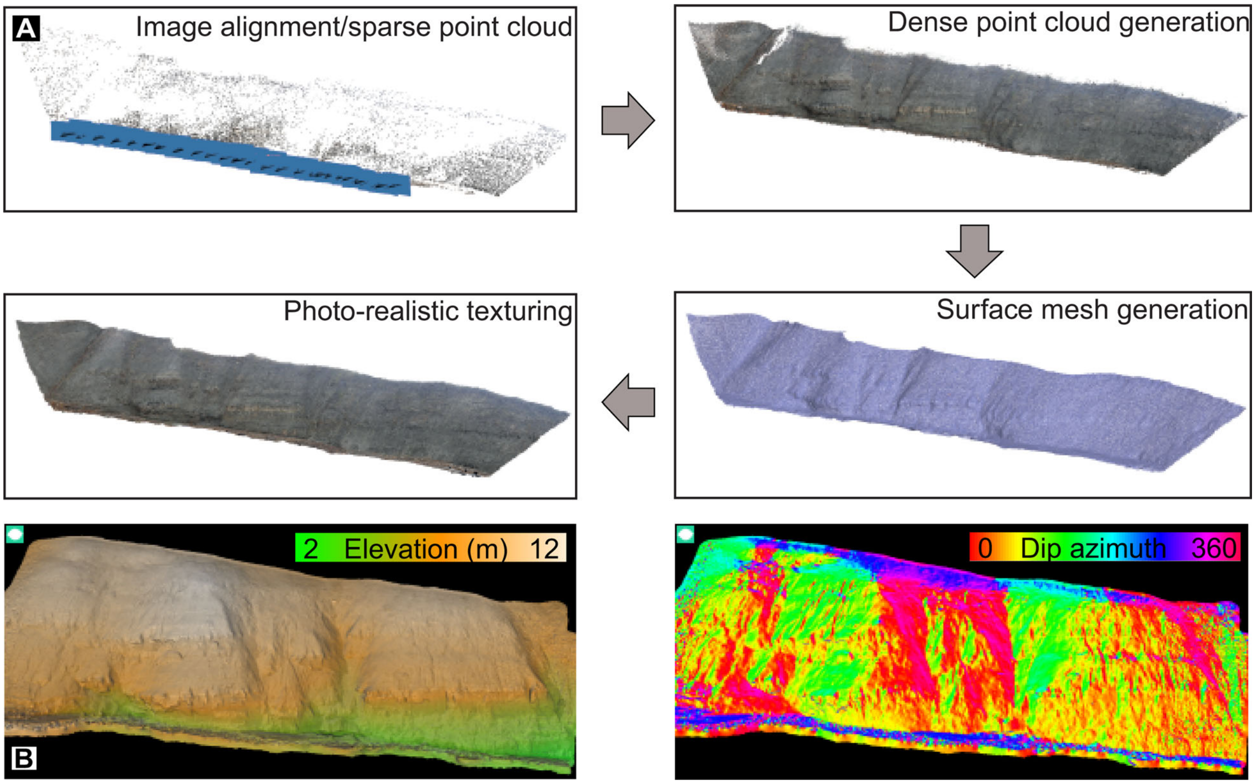

Figure 7. (A) Sequential structure-from-motion processing work flow, from images to a photo-realistic geo-referenced 3D digital outcrop model of Konusdalen, Svalbard. The resulting model is available in 3D.pdf format in Appendix I. (B) Examples of analyses of digital outcrop models.

that can be used for visualization or further analysis, including recording accurate geo-referenced measurements. Common practice in the geology bachelor program at UNIS is to import models into LIME (Buckley et al., 2019), which facilitates measuring length and vertical distance between points and orientated surface azimuth/dip calculated from three point selections. The 3 D models allow accurate measurements to be recorded, whereas panoramic imagery (e.g. GigaPan) is subject to barrel distortion and therefore measurements from image extremities will be underestimated. The line interpretations can be imported into 3 D geomodelling software (e.g., Petrel, MOVE) to generate surfaces and geological models. Anell et al. (2016) thus identified low-angle deltaic geometries (ca. 150-200 m high and 10-20 km long clinoforms) from a 45-km long DOM of southern Edgeøya, Svalbard, features usually only identifiable in seismic data. This model has allowed for modeling synthetic seismic which effectively shows that the faults, lenticular shaped sandstone bodies and horizontally orientated igneous bodies (sills) at that locality would indeed be identifiable in high-resolution seismic studies (Anell et al., 2016). As part of AG222, bachelor students learn to create synthetic seismic images on the basis of DOMs. In this context, we put an emphasis on how seismic frequency and illumination affect the representation of geological features in the resulting image (Lecomte et al., 2015). Automated and manual fracture mapping is also possible using DOMs (Casini et al., 2016; Larssen, 2018; Mulrooney & Senger, 2016) and can potentially reduce the need for prolonged manual data collection in the field if DOMs are properly calibrated with field data. 3 D models of fractures or faults also allow analysis of the structures' roughness across a range of scales (Corradetti et al., 2017; Olkowicz et al., 2019). Similarly, dip of sedimentary bedding or even of single clasts can be measured directly from DOMs (Berg, 2018). Photogrammetry can also be used to generate digital (real-scale) representations of geo-referenced samples (De Paor, 2016) or drill cores (Betlem et al., 2020).

DOM: Mapping user experiences

During the 3-year long development stage, we focused on testing and optimizing the various components that collectively make up the Svalbox database. In addition we collected qualitative data on how the project team and students experience DOMs to further optimize its use. Firstly, we review the proficiency that different user groups have at different parts of the DOM workflow (Figure 8). While the survey population is somewhat limited (n = 36), particularly for petroleum industry professionals, a few interesting trends already emerge. Ground control point (GCP) acquisition, data sharing and DOM editing are consistently low-scoring parts of the workflow across the user groups. As proficiency is primarily an effect of actively using the workflows this is likely related to users not using GCPs, editing DOMs or sharing data. On the high-end of the proficiency scale are both photo acquisition and DOM interpretation.

Table 3 lists the benefits and challenges of using DOMs and it is apparent that the benefits significantly outweigh the challenges (123 benefits reported, 64 challenges reported). In particular, the ability to conduct quantitative analyses (80% of respondents) and extending the field season

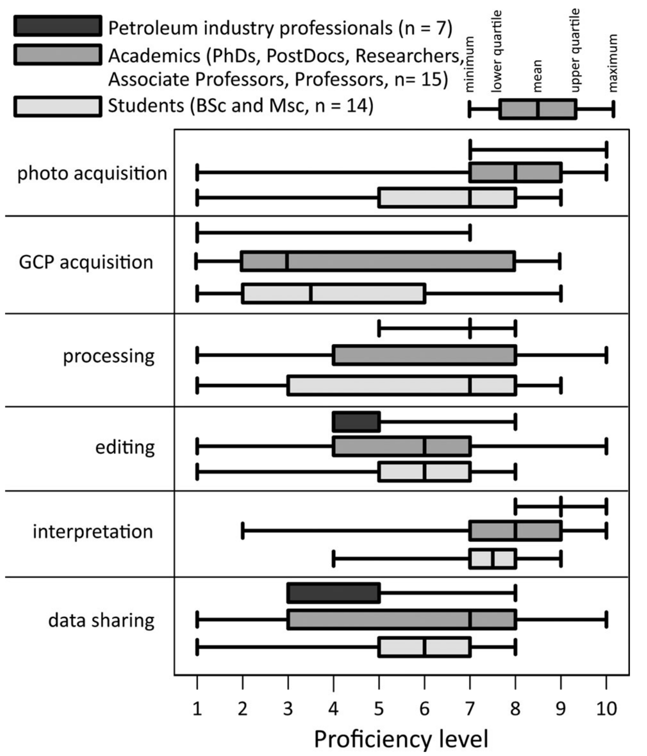

Figure 8. Synthesis of proficiency levels within the DOM workflow, subdivided by user groups.

(75%) are near-universal benefits. Approximately half of the respondents benefited from elements such as: appreciation of scale, data sharing, DOM integration and having a reference of the outcrop. User-driven feedback includes the fact that DOMs allow the ability to carry out detailed analyses of outcrops that may not be accessible in the field and the ability to exaggerate the vertical scale and thus appreciate truncation relationships that may be missed. Turning to the challenges, 44% of respondents consider the necessity of expensive hardware the biggest challenge in utilizing DOMs. Approximately one third highlight the lack of easily accessible interpretation software and the difficulty of the processing workflow, while a quarter consider acquisition-related aspects and adequate geo-referencing problematic. Additional challenges identified by single respondents include the fact that processing for mm-scale high resolution models necessary for sedimentology is extremely slow, irrespective of hardware, DOMs are challenging to use offline, lack of training possibilities, the risk of collecting too much data and that ground-truthing is often overlooked. We can only speculate on why users consider collecting too much data to be problematic, but from our personal experience this may be related to the fact that extensive DOM collection takes away precious fieldwork-time from, for instance, conducting detailed geological observations. Ground-truthing relies on field visits to check whether lithologies interpreted on DOMs prior to the field campaign are correct, and is usually based on sedimentological logs. Many of the challenges raised by the users are surmountable, for instance with a server-based configuration of the processing computers that significantly enhanced processing time for high-resolution DOMs to several hours.

Educational mobile applications and software

We have compiled a non-exhaustive list of relevant smartphone applications, geoscientific software and e-learning modules currently used at UNIS, and provide these online through the Svalbox website's e-learning section (https://svalbox.no). These include the SvalSIM geosimulator (Saether et al., 2004), the LIME DOM interpretation toolbox (Buckley et al., 2019) and the Google Earth platform (Bailey et al., 2012; Giorgis, 2015; Lisle, 2006; Monet & Greene, 2012). In addition, numerous tools available on smartphone and tablets can be used to collect georeferenced observations and quantitative data in the outdoors (e.g., Allmendinger et al., 2017; Kehl et al., 2017; Novakova & Pavlis, 2019; Weng et al., 2012; Zervas et al., 2009).

Highlights and challenges of Svalbox development

Svalbox's initial development steps involved extensive research, trial and cataloguing of "off-the-shelf" software, hardware, data sets (e.g., geological maps, topographic maps) and other resources to facilitate geoscientific learning (presented in Svalbox; Figure 9). This time-consuming stage was conducted primarily by the instructor, but students in various courses were encouraged to use some of the field-based applications and products in their studies, and also provided some feedback. An outcome of this process is "the digital field notebook", which comprises field-proof tablets loaded with a selection of applications designed to increase the effectiveness of fieldwork (Senger & Nordmo, 2020).

The biggest challenge with respect to such off-the-shelf tools is that many good tools, particularly those developed by academics, are often discontinued due to the large maintenance costs and lack of time. In addition, workflows to conduct relatively mundane tasks such as importing basemaps to tablets, producing 3 D terrain files for 3 D printing or displaying geo-referenced geological maps with a legend are a cumbersome process and must be documented by clear and accessible step-by-step guidelines to avoid frustration. We have over time developed an internal Wiki-style platform dedicated to sharing such workflows amongst staff and students, and envision sharing it through Svalbox in the near future. Data management, in particular data integration, remains challenging. Most of the Svalbox data, with the exception of the DOMs (their position is included), is accessible internally at UNIS in a Petrel and ArcGIS project. However, students still need site-specific projects when interpreting DOMs and can only do so using top-end computers which are relatively expensive.

The course teachers found that while the DOM acquisition to interpretation workflow is reasonably quick for the students to comprehend and utilize, processing their own (or mostly provided) photographs to generate high quality DOMs is more challenging. This is partly attributed to the course scheduling with limited access to snow-free outcrops, and the need to gain some experience by hands-on processing by the students themselves. In addition, the students often struggle to define the quality of a given DOM, which is determined by the outcrop size, chosen resolution and

Table 3. Benefits and challenges of digital outcrop models.

What do you see as the main benefits of using digital outcrop models?	N	%
Ability to conduct quantitative analyses	29	80.6
Extended field season	27	75.0
Appreciation of scale	18	50.0
Sharing data with colleagues, supervisors etc.	18	50.0
Integrate outcrop data with other geo-referenced data sets	16	44.4
Having a reference of the outcrop (such as in publications)	15	41.7
What do you see as the main challenges to using digital outcrop models?	**N**	**%**
Requires expensive hardware	16	44.4
Interpretation software not easily accessible	12	33.3
Processing workflow is difficult	10	27.8
Adequate geo-referencing	10	27.8
Data acquisition aspects	9	25.0
Data sharing and data availability	4	11.1
Scale is difficult to comprehend	3	8.3

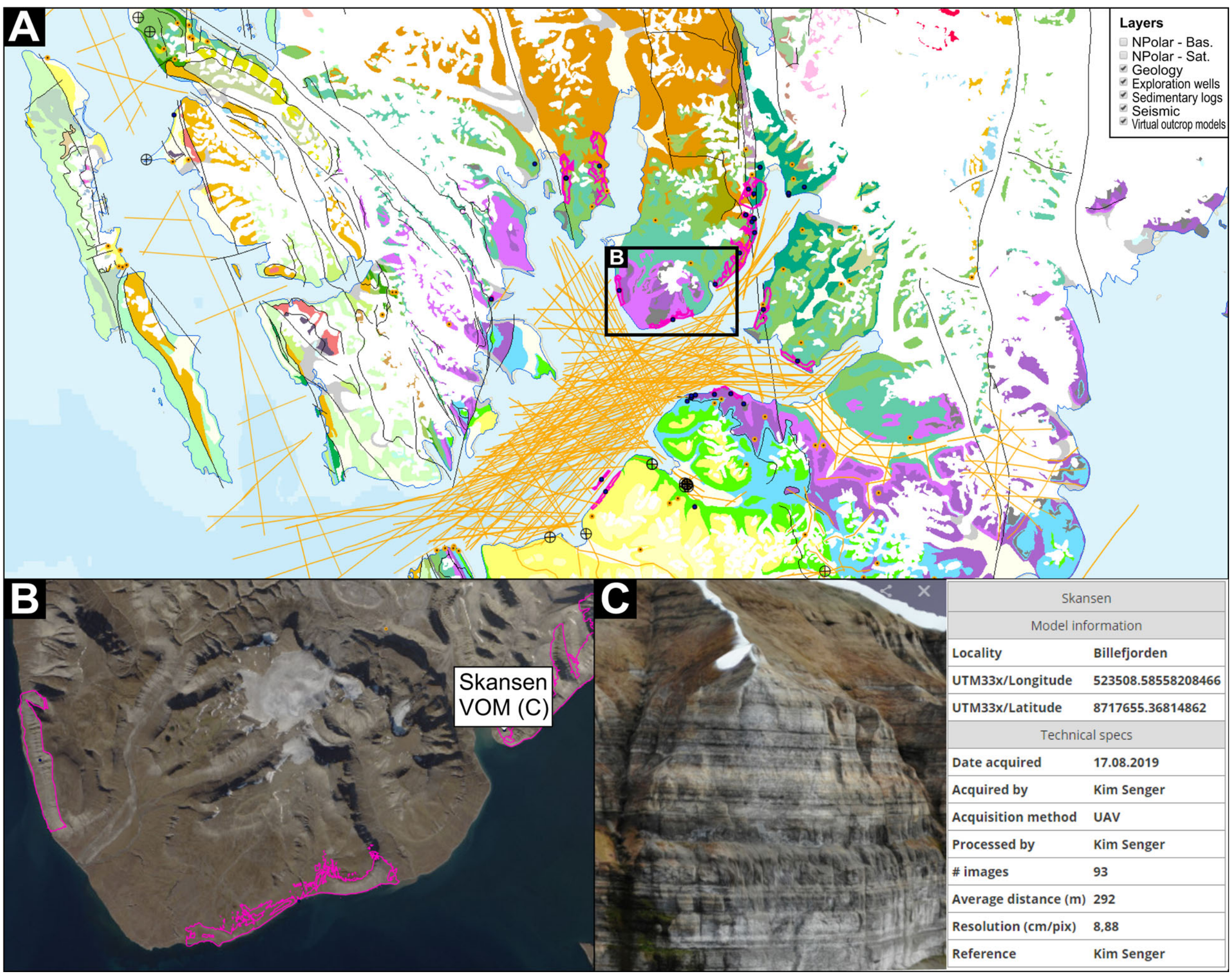

Figure 9. The online map-based public-domain interface on Svalbox.no. (A) Data coverage in central Spitsbergen, including digital outcrop models (pink), seismic lines (orange lines) and sedimentary logs (orange points). The base map shows the geological map, courtesy of the Norwegian Polar Institute. The interactive layer list allows the selection of various data types. (B) Detailed view of southern Dickson Land, and the location of the Skansen virtual outcrop model. The satellite image base map is streamed from the Norwegian Polar Institute's Geodata portal. (C) Example of the Skansen virtual outcrop model embedded on the Svalbox website, with key acquisition parameters.

practical usability. Students often process large DOMs at maximum resolution, which makes processing slow and the resulting models too sizeable for the DOM interpretation software. Furthermore, they are required to carry out their processing at a similar time to one another which further limits computing capacity. Dividing larger models into smaller high-resolution sub-models is the preferred solution, as is server-based processing.

Students and lecturers reported that utilizing DOMs for student training and education is positive (Table 3). DOMs are highly interactive visualization of data which we utilized in the classroom for training students in outcrop observation and interpretation techniques and teaching regional geology. Furthermore, students and researchers have used them to study specific problems in structural and sedimentary geology, facies analysis and many others. We have also found that the use of DOMs further enables critical thinking, particularly drawing attention of the students to the differences between geological observations and derived geological interpretation as an exact scientific method. The interactive nature of DOMs is a very useful tool to trigger discussions within the student groups and with the lecturer, and to motivate and support the students' self-learning approach. The dynamics in group discussions often differs in comparison to in-field discussions and can, therefore, be utilized as an additional tool in didactic methods in geosciences education. We have found that the visualization possibilities of 3 D photorealistic DOMs particularly useful in structurally complex geological settings, where having multiple perspectives is extremely useful.

The benefit of Svalbox compared to other exercise sets is that the database is directly relevant for to-be-visited field sites. It is possible to construct exercises on data from the field localities or relevant nearby comparisons (e.g., offshore seismic data related to the onshore geology they will see in outcrop). It also allows (quality-controlled) student-collected data to be integrated into the database, thereby increasing the students' authentic experience of contributing to our knowledge database from participating in the course fieldwork.

Future perspectives

The Svalbox concept is only as good as the data and solutions attributed to it. As such, the project must be dynamic and continuously growing, with this article providing a snapshot following Phase I of the Svalbox project. Over time, we envision the inclusion of additional data types (e.g., geological profiles, GeoTiffs, 360° imagery, drone overview videos) in the online data portal, as well as regular updates of new content (e.g., relevant publications, virtual field trips; Senger, 2019a) and data types (e.g., hand samples, digital drill cores; Betlem et al., 2020). Data acquisition, particularly more DOMs, ground-control data acquired through sedimentary logging and shallow geophysical data sets (e.g., georadar and geoelectric profiles; Betlem & Senger, 2018) will also be incorporated to Svalbox. Such data acquisition campaigns can provide an added educational benefit for the students involved, and yield more data for the database.

A key mid-term objective is facilitating the offline use of Svalbox directly in the field, as part of the digital field notebook concept (Senger & Nordmo, 2020). This is particularly important with regards to the DOMs. Furthermore, applications exist that can display high-resolution DOMs on tablets (e.g., Emb3D), but current software unfortunately requires data-transfer workflows that are often counter-intuitive or relying on internet connectivity. Other innovative future aspects include 3 D printing of terrain models or DOMs to improve spatial thinking, as have been successfully used for 3 D printing of extra-terrestrial bodies (Horowitz & Schultz, 2014). Virtual reality systems, some of which being battery-powered and portable, may also facilitate the perception of scale which is often lost on PC screens, where data are routinely shown with large vertical exaggeration.

The global Covid-19 pandemic has propelled the usage of Svalbox as a teaching tool in the AG222 course, which had to be finalized without field excursions in spring 2020. Instead, a 2-day virtual field excursion was organized to the Billefjorden Trough (http://Svalbox.no; Senger et al., 2020). Students used Svalbox to prepare "geological stops" to present to their peers in an online environment, and to complete a post-excursion exercise where the integration of all provided data sets was paramount. This experience illustrated the suitability of utilizing Svalbox for fully digital courses, without the need for field visits and irrespective of the physical location of the instructors and the students. In addition, the virtual field trip has exposed potential improvements – primarily the need for more outcrop-scale and hand-sample scale DOMs, and seamless integration of multi-scale DOMs and related data (sedimentary logs, outcrop overview photos, digital field data) – which are being solved in an ongoing Svalbox upgrade.

Nonetheless, field geology is grounded in the senses that, apart from observing, there will always remain a need for touching, smelling, hearing and, sometimes, even tasting the rocks. The power of databases like Svalbox should lie in integrating the physical experiences of examining rocks within a broader framework set up by the complementary data sets. DOMs (and digital sample models) are a prime example of complementary data sets that we foresee as becoming a common method for geoscientists within the near future, similarly used as photo documentation. As such, geoscientific education must include a component of digital geological tools to adequately prepare the students for their professional careers.

Conclusions

In this commentary, we present our experiences of using a range of digital tools in geoscience education in the high Arctic, namely in Svalbard, using the Svalbox data integration and sharing portal. These experiences and learnings include:

- testing numerous off-the-shelf software and smartphone applications that can be used in harsh Arctic conditions and in the classroom setting;
- optimizing workflows for generating and interpreting digital outcrop models (DOMs) at a range of scales, and teaching these to our students through practical activities
- integrating surface and subsurface geoscientific data in a 3D-environment, through use of the Svalbox database;
- sharing DOMs from Svalbard with the general public through an online interface, the Svalbox online portal;
- applying the advantages of digital methods such as DOMs as powerful complementary tool for field teaching and outcrop studies particularly for areas with limited access in the high Arctic; and
- examining how these digital tools can facilitate student experiences prior, during and following fieldwork.

The Svalbox database, actively used by university-level geoscience courses at UNIS, provide a foundation to optimize the use of modern geoscientific tools in higher education and also quantify their effect on the students' learning process and learning outcomes.

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ORCID

Kim Senger http://orcid.org/0000-0001-5379-4658
Simon J. Buckley http://orcid.org/0000-0001-8680-8286
Bernard Coakley http://orcid.org/0000-0002-5592-533X
Peter P. Flaig http://orcid.org/0000-0002-4702-2157
Maria Jensen http://orcid.org/0000-0003-2711-3606
Isabelle Lecomte http://orcid.org/0000-0002-3316-535X
Rie Hjørnegaard Malm http://orcid.org/0000-0002-4323-3491
Aleksandra Smyrak-Sikora http://orcid.org/0000-0001-9321-1269

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