1. Introduction

Analyzing outcrops is a fundamental technique in many contemporary geological investigations. Digitalization of outcrops, in particular, complements conventional outcrop analysis, allowing for quantitative digital assessment. Digital outcrop models (DOMs) represent a georeferenced 3D view of an outcrop with mm-to dm-scale. DOMs can, therefore, incorporate topographical data of various scales, bridging the gap between centimeter-scale local observations and hundreds of meters-scale seismic structures (Enge et al., 2007). DOMs are becoming a popular tool in geosciences and their advancement over the past two decades has been significant (Buckley et al., 2008, 2019; Carrivick et al., 2016; Enge et al., 2014). However, the expensive nature of the equipment and acquisition and lengthy processing procedures, limited its widespread adoption in academia. More recently, the rapid evolution of structure-from-motion (SfM) algorithms and their implementation in user-friendly software, has led to an explosion of digital models from a wide variety of sources (Bemis et al., 2014, Carrivick et al., 2016; James et al., 2019; Smith et al., 2016; Westoby et al., 2012). In summary, the increased availability of cost-effective consumer-grade drones with a built-in Global Positioning System (GPS) and high-quality cameras provides a new and potentially game-changing tool for geoscientists (Bemis et al., 2014; Nesbit et al., 2018). Additionally, DOMs are becoming increasingly valuable for teaching and planning geological field campaigns (McCaffrey et al., 2016; Senger et al., 2020).

Another widely used technique for shallow subsurface investigations on land is ground penetrating radar (GPR). GPR allows geoscientists to acquire up to cm-scale 2D or 3D geological models of the subsurface (Asprion and Aigner, 1999; Huggenberger, 1993; Kostic and Aigner, 2007). GPR is commonly used to map modern karst caves and paleokarst breccias, allowing the detailed study of their internal and external structures (Chalikakis et al., 2011; Chamberlain et al., 2000; McMechan...
GPR, along with other ground-based geophysical methods, are tools that meet the challenges originating from lateral and vertical changes of the physical and lithological properties of karst environments, quaternary coastal deposits and coastal barriers (Chalikakis et al., 2011; Jol et al., 1996; Neal et al., 2002).

The integration of GPR with outcrop data enables geoscientists to extend 2D outcrops from the rockface to a third spatial dimension. Despite the advantage of modeling 3D subsurface geometries derived from a GPR grid, this has rarely been performed. Limited case studies have been published on tidal channels, turbiditic sequences and river bar deposits (Subeck et al., 2011; Jones et al., 2011; Korus et al., 2020; Lee et al., 2007; Pringle et al., 2003, 2006; Wheeler et al., 2011; Young et al., 2003). Luthi and Flint (2014) and Pierce et al. (2018) used shallow borehole data from behind outcrops to extend the knowledge of reservoir architecture but are spatially limited to the well location. Jones et al. (2011), Fernandes et al. (2015); Martinez et al. (1998); Wheeler et al. (2011) and Young et al. (2003) have shown that GPR can be used to extend outcrop analysis into the nearby subsurface. Studies have utilized geophysical techniques to analyze paleokarst (e.g. Chalikakis et al., 2011; Wheeler et al., 2011), but they have not been directly tied to outcrop.

Paleokarst is a term applied to karst deposits that have been disconnected from the active hydraulic system at some point in time and have been buried by younger rocks. Paleokarst systems are a typical feature in sedimentary basins and in particular in rift basins that comprise evaporitic sequences (Anderson et al., 1978; Blatnik et al., 2020; Blount and Moore, Jr., 1969; Friedman, 1997; Klimchouk et al., 1996; Sayago et al., 2012; Swennen et al., 1990; Tian et al., 2019; Zeng et al., 2011). Here, paleokarst systems mainly develop along faults, fracture networks and bedding planes, showing that active faulting promotes dissolution and subsequent collapse (Palmer, 1991). Paleokarst deposits are strongly heterogeneous and complex with regards to rock texture, structure and pore networks (e.g. Loucks, 1999; Loucks and Mescher, 2001) and are reservoirs in petroleum systems.

The Upper Paleozoic Billefjorden Trough in Svalbard is an example of a rift basin containing thick evaporite sequences and associated paleokarst collapse breccia (Eiassen and Talbot, 2005). The paleokarst system of the Billefjorden Trough is considered as an outcrop analogue to prolific paleokarst plays in the Barents Sea (Eiassen and Talbot, 2005; Sayago et al., 2012; Solbakk 2020). Both the Gohta (well 7120/1–3) and the Alta (well 7220/11–1) oil discoveries in the Loppa High on the Barents Shelf south of Svalbard are in karstified carbonates of Late Paleozoic age (Matapour et al., 2019), and one recent exploration well on the Selis Ridge (well 7221/4–1) targeted these karstified carbonates (Fig. 1A; “NPD FactMaps Desktop”, 2020; Solbakk, 2020). Therefore, investigations of the paleokarst system of the Billefjorden Trough may play a role in mitigating risk related to exploration on the Barents Shelf and similar basins.

In this case study we investigate the Billefjorden Trough paleokarst system at Rudmosepynten in inner Billefjorden, Svalbard (Fig. 1B,C), by combining a GPR dataset with a DOM and conventional geological data from an extensive paleokarst outcrop near the Fortet locality. In addition, we propose a workflow for DOM and GPR processing, as well as the integration of outcrop data with DOMs and GPR. This approach enables us to link sedimentary facies observed in the outcrop to GPR facies.

2. Geological setting

In central Spitsbergen, the north-south striking Billefjorden Trough consist of up to 2000 m thick, westward thickening, mixed syn-rift successions of siliciclastics, evaporites and carbonates (Braathen et al., 2011; Harland et al., 1997; Johannessen and Steel, 1992; Smyrak-Sikora et al., 2019). These units were deposited in arid to semi-arid climate conditions in Carboniferous times (Late Serpukhovian-Moscovian) (Cuttill and Challinor, 1965; Holliday and Cutbill, 1972; Johannessen and Steel, 1992). The overlying post-rift succession of Late Carboniferous-Permian age consists of up to 100 m thick interbedded carbonate-and evaporite-platform deposits that cover most of central Spitsbergen (Sorento et al., 2020).

The Billefjorden Trough formed on the hanging wall of the Billefjorden Fault Zone (BFZ) - a crustal-scale boundary between Devonian sedimentary units to the west and metamorphic pre-Caledonian basement to the east (Braathen et al., 2011; Harland et al., 1997). During the Carboniferous, the BFZ reactivated as a normal fault in response to regional extension (Faleide et al., 1984; Harland et al., 1974). The Carboniferous deformation comprises a set of syn-depositional faults formed along the hanging wall block, antithetic to the BFZ (Braathen et al., 1998).
Minor, post-rift fault activity along the BFZ persisted into the Permian (Ahlborn and Stemmerik, 2015; Maher and Braathen, 2011; Stemmerik and Worsley, 2005). In the Paleogene, during the Eurekan transpressional tectonic event, several of these faults were reactivated as reverse faults (Bælum and Braathen, 2012; Bergh et al., 2000; Braathen et al., 1999; Haremo et al., 1990; Manby et al., 1994; McCann and Dallmann, 1996).

The deposition of the syn-rift strata within the Billefjorden Trough initiated in Serpukhovian with the accumulation of siliciclastic red beds of the Hultberget Formation, interpreted as terrestrial fluvial and overbank deposits (Johannessen and Steel, 1992). The Bashkirian aged Ebbadalen Formation is interpreted as being paralic, with units consisting of terrestrial to shallow marine siliciclastic deposits, gypsum beds formed in sabkhas and salinas, and restricted to open marine carbonates deposited and intercalated with black shales (Holliday and Cutbill, 1972; Johannessen and Steel, 1992; Smyrak-Sikora, 2020; Smyrak-Sikora et al., 2019).

The Minkinfjellet Formation (Fig. 2) comprises up to 500-m-thick beds of gypsum and carbonates with subordinated sandstone layers (Eliassen and Talbot, 2003b; Smyrak-Sikora, 2020; Verba, 2013). The unit was deposited in a shallow, tidally influenced marine basin environment, onlapping the Ny Friesland High to the east (Dallmann, 1993; Eliassen and Talbot, 2003b; Løy, 1995). The overlying syn-to-post-rift
Fig. 3. Stratigraphic log through the Minkinfjellet carbonates and the paleokarst breccias at Rudmosepynten. A: Paleokarst breccia, lithofacies B. B: Clay layer at the base of the paleokarst breccias, lithofacies B. C: Section of wackestone and chert beds in lithofacies A. D: Dolomitic section in lithofacies A. E: Calcite nodule in dolomitic section of lithofacies A. F: Dolomite nodules and styloliths in packstone section of lithofacies A. G: Image of the outcrop showing the locations of the images. The trace of the stratigraphic log is highlighted by the thick sections of the white line. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Wordiekammen Formation is a carbonate dominated succession that extends regionally over the flanks of the Billefjorden Trough (Braathen et al., 2011; Dallmann, 1999; Pickard et al., 1996). These formations commonly display oil staining and exhibit a strong hydrocarbon odor, presumably generated from the organic-rich lagoonal carbonate mudstones which were deeply buried until the past few Myr (Henriksen et al., 2011a; Nicolaisen et al., 2019).

The Fortet Member, the focus of this study, is a locally developed member of the Minkinfjellet Formation and consists of carbonate breccia, formed by karstification of the carbonate-evaporite succession

### Table 1
Acquisition parameters for the photogrammetric and GPR survey.

| Photogrammetry parameters | Ground penetrating radar parameters |
|---------------------------|------------------------------------|
| Acquisition type          | Drone                              |
| Type model                | DJI Mavic 2 Pro                    |
| Camera                    | Built-in 20 Megapixel              |
| Georeferencing            | Ground calibration points          |
| Recording format          | Video                              |
| Recording parameters      | 1920 x 1080 @30 fps                |

| Acquisition parameters | Ground penetrating radar parameters |
|------------------------|------------------------------------|
| Antenna configuration  | In-line parallel                   |
| Antenna frequency      | 50 MHz                             |
| Receiver offset        | 2 m                                |
| Transmission trigger   | Time triggered                     |
| Time interval          | 0.01 s                             |

### Table 2
DOM specific parameters. Modified from Janocha (2020).

| Model          | Original number of images | Number of processed images | Ground resolution | Distance to outcrop | Covered area |
|----------------|---------------------------|----------------------------|--------------------|---------------------|--------------|
| Rudmosepynten  | 1222                      | 458                        | 0.7 cm/pix         | 17.3 m              | 2 310 m²     |
| Overview       | 124                       | 124                        | 14.6 cm/pix        | 621 m               | 587 000 m²   |
| South Central  | 949                       | 415                        | 1.3 cm/pix         | 35.6 m              | 4 440 m²     |
| South East     | 2 053                     | 898                        | 1.2 cm/pix         | 35.6 m              | 5 990 m²     |
| East           | 88                        | 88                         | 1.2 cm/pix         | 26.8 m              | 664 m²       |
| Block East     | 99                        | 99                         | 0.9 cm/pix         | 18.8 m              | 351 m²       |
| North          | 1 141                     | 645                        | 1.5 cm/pix         | 46.8 m              | 5 880 m²     |
| Pinnacle       | 922                       | 445                        | 1.8 cm/pix         | 54.3 m              | 293 m²       |
| Block West     | 185                       | 185                        | 1.7 cm/pix         | 53.3 m              | 549 m²       |
| Caves          | 983                       | 485                        | 0.7 cm/pix         | 19.2 m              | 2 010 m²     |
| Gypsum breccia | 262                       | 262                        | 1.1 cm/pix         | 67.6 m              | 6 660 m²     |

Fig. 4. From outcrop to digital outcrop model: Processing steps. A: Aligning photos. B: Sparse cloud. C: Dense cloud. D: Mesh of triangulated surfaces. E: Textured layer from pictures draped on mesh. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
of the Minkinfjellet Formation and upper part of Ebbadalen Formation (Fig. 2B). This occurred due to the dissolution of gypsum beds (Eliassen and Talbot, 2003b; Lønøy, 1995). Two types of paleokarst breccia have previously been recognized: (i) vertical cross-cutting bodies (pipes) (Fig. 2C) located along faults (i.e. Løvehovden Fault Zone) were interpreted to have formed in the Early Permian, during a post-rift phase of the Billefjorden Trough (Eliassen and Talbot, 2003b, 2005); (ii) horizontal strata-bounded breccias (Fig. 2C) (Eliassen and Talbot, 2003b, 2005) located along the flanks of the Billefjorden Trough formed during the Late Carboniferous, due to syn-depositional uplift along fault blocks (Smyrak-Sikorn, 2020). Eliassen and Talbot (2003a) suggest that the dissolution and brecciation observed within the Minkinfjellet Formation is related to periods of subaerial exposure occurring contemporaneously with the deposition of the overlying Wordiekammen Formation (Fig. 2). Evidence for continuous deformation during and after the deposition of the paleokarst breccias occur as faults in the breccias of the Fortet outcrop (Janocha, 2020).

3. Methods and data

3.1. Lithofacies

All the associated data presented in this study are collected from the Rudmosepynten outcrop area near the Fortet locality in the innermost
part of Billefjorden (Fig. 1B,C). This is the type locality for the Fortet Member, in which the investigated breccias occur. The Rudmosepynten outcrop stretches in east-west direction over 300 m along the coastline at Rudmosepynten. With a height of approximately 10 m it forms a cross-section through the adjacent plateau. Detailed stratigraphic logging and sedimentological descriptions are used to describe the outcrop and define lithofacies. A 30 m long sedimentological log in 1:50 scale was collected along the Rudmosepynten outcrop that represent lithofacies A and B (Fig. 3).

3.2. Digital outcrop models (DOMs)

The photogrammetric models are based on videos from a GPS-enabled drone (Table 1). To ensure sufficient image overlap, the drone was flown at a constant speed (5 m/s) along the outcrop while recording video. Every 15th frame was extracted from each video using Agisoft Metashape Professional software (Agisoft, 2020). For georeferencing the Rudmosepynten DOM, four ground control points were placed along the outcrop and their position was determined with a Garmin eTrex 10 GPS connected to the MÅLA CV monitor. The antennas emit electromagnetic waves in the range of 10s to 100s of MHz. The vertical resolution in GPR is fully dependent on the emitted wavelength in the subsurface (Equation (1)). These waves are then reflected by contrasts in electro-magnetic permittivity in the subsurface. GPR

Fig. 6. Draping GPR profile 2 over the Rudmosepynten DOM. A: DOM of the outcrop. Showing the eastern most section of the DOM. B: closeup on the paleokarst breccias of lithofacies B. C: Closeup on the dipping carbonate layers of lithofacies A. D: GPR profile 2 acquired 3 m behind and parallel to the outcrop. E: Data integration by draping the GPR profile on the model in LIME. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

A supplementary video summarizing the article with additional Figures and visual explanations can be found at https://doi.org/10.1016/j.marpetgeo.2020.104833
acquisition was carried out in April 2018 on snow covered ground. The snow cover and frozen active permafrost layer allowed fast acquisition with no environmental impact on the vegetation and soil. To account for the offset between the GPS and the GPR antennas, a MATLAB script corrected the location of every GPR trace regarding this offset. Processing of data was performed using the ReflexW (software) (Sandmeier, 2019) following the processing steps in Senger et al. (2014), who investigated structural heterogeneity in Jurassic sandstones in Svalbard, using the same equipment. The basic processing involved moving the first arrival to the top of the profile (Fig. 7B), dewow filtering (Fig. 7C), accounting for attenuation by applying an energy decay function (Fig. 7D). Furthermore, the airwave was reduced by a background removal (Fig. 7E). A time-depth conversion (Fig. 7A) with a constant velocity of 0.12 m/ns (Robinson et al., 2013) was used to display the y-axis as depth instead of two-way-travel time. 

vertical resolution = \frac{\text{wavelength}}{4} \quad (1)

In this contribution, we focus on 13 GPR profiles with a total length of 1.4 km. These GPR profiles were acquired directly on top of the Rudmosepynten outcrop, including 9 profiles striking outcrop-parallel and 4 outcrop-perpendicular (Fig. 5B). GPR profile 2 (Fig. 6B) represents an outcrop-parallel profile acquired approximately 3 m behind the outcrop, whereas GPR profile 12 represents an outcrop-perpendicular profile acquired towards a talus slope (Fig. 5B).

3.4. Data integration

Integration of the DOM and GPR survey was carried out in the LIME virtual outcrop interpretation software, version 2.1.9.1 (Buckley et al., 2019). These interpretations are based on visual observations and limited by mesh resolution and DOM resolution. Fig. 8 visualizes the steps from image and GPR acquisition, DOM and GPR processing to DOM and GPR integration. To load the DOMs into the interpretation software the DOM is required to be in UTM coordinates. The GPR profiles were imported to LIME as image panels. These panels were manually placed within the working environment using the start and end coordinates of the GPR profile.

4. Results and interpretation

4.1. Facies description and interpretation

The different facies types described from outcrop and DOM observations are lithofacies A, B and C, in the GPR profiles GPR facies A, B and C are observed. Lithofacies B and GPR facies B are overlying and younger than lithofacies A and GPR facies A.

4.1.1. Facies A

**Description of lithofacies A:** In outcrop lithofacies A consists of interbedded wackestones, packstones, dolomites and mudstones with clear bedding thickness of 10 cm to 1 m. Lithofacies A is of carbonate composition and has a strong smell of hydrocarbons. The upper part of the outcropping succession is dominated by parallel bedding whereas the lower part exhibits sinusoidal bed geometries. The color of lithofacies A is the same dark grey as the clasts of lithofacies B (Fig. 3C-E and Fig. 9A,B). The interval gently dips to the west with an inclination of 16°. In the DOM lithofacies A is easily identifiable by its characteristic westward titled carbonate benches (Fig. 9A,B). All but the thinnest intervals of lithofacies A are resolvable in the DOM.

**Description of GPR facies A:** GPR facies A dominates the eastern part of the survey area (Fig. 9C and Fig. 10C,D). It is characterized in the GPR data by stronger, coherent and continuous westward-dipping reflectors. GPR facies A appears to sharply underlie GPR facies B. GPR facies A shows slightly deeper (0.5 m) GPR penetration than GPR facies B.

**Interpretation of Facies A:** Lithofacies A is interpreted to represent carbonate benches of the Minkinfjellet Formation. Strata of this lithology is also the likely source of carbonate wackestone and packstone clasts that dominate the paleokarst breccia of lithofacies B. Lithofacies A was deposited in a shallow marine, tidally influenced basin and was
deposited prior to lithofacies B (Eliassen and Talbot, 2003b). The contact of lithofacies A to lithofacies B is interpreted as the base of the paleo-cave system. In the GPR profiles the contact between GPR facies B and GPR facies A is marked by a sharp boundary. This boundary is dip parallel to the dipping reflectors of GPR facies A. This prominent reflector correlates well with measurements of the outcrop contact which makes it an ideal candidate to analyze the distribution and geometry of the paleo-karst system in the GPR data.

4.1.2. Facies B

Description of lithofacies B: Lithofacies B exclusively dominates the western section of the outcrop. In outcrop, lithofacies B appears as a chaotic clast-supported conglomerate. No obvious depositional structures were observed with regards to clast distribution or the matrix. The conglomerate consists of (very poorly sorted) micritic (sub-rounded to sub-angular) clasts and are 2–10 cm large (Fig. 3A and Fig. 9D,E). The matrix is composed of clay grade material of dark grey coloration. Both the clasts and matrix have a carbonate composition. The transition from lithofacies A to the overlying lithofacies B is marked by a sharp dip...
parallel boundary. Directly at the contact to lithofacies A this facies has a thin (10 cm) clay layer (Fig. 3B). In the DOM, lithofacies B is identifiable by the lack of stratification. Some smaller clasts are indistinguishable in the DOM despite a resolution of 0.7 cm/pixel due to the similarity in clast color and appearance.

**Description of GPR facies B**: GPR facies B is prominent in the GPR profiles and dominates the western parts of the survey area (Fig. 9F and Fig. 10C,D). It is characterized by discontinuous and often chaotic reflectors. GPR facies B typically shows a dimming response in comparison to the surrounding intervals. The transition from GPR facies B into GPR facies A is typically abrupt and coherent.

**Interpretation of facies B**: The conglomeratic composition of facies B and its sharp boundary to facies A (as described above) is interpreted as a dissolution collapse breccia (Friedman, 1997; Klimchouk et al., 1996; Loucks, 1999). Gypsum clasts are observed in the Fortet Member in other parts of the basin so is almost certainly the dissolved mineral responsible for brecciation (Eliassen and Talbot, 2005). The local geology and overview DOM also suggest that this facies is a component of a larger karst system that has been subsequently buried; therefore, facies B is classified as a paleokarst breccia. Paleo-cave roof collapse and clast transportation within the paleo-cave resulted in the deposition of a breccia with sub-rounded clasts.

**Fig. 9.** Description and interpretation of facies A and B. Comparison of observations made on facies A and B in the field, the DOM and GPR. A: Outcrop picture of lithofacies A. B: Exported image of lithofacies A from DOM. C: Section of GPR facies A in GPR profile 2. D: Outcrop picture of lithofacies B. E: Exported image of lithofacies B from DOM. F: Section of GPR facies B in GPR profile 2. Orientations are presented in azimuth/dip angle convention throughout the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
4.1.3. Facies C

Description of lithofacies C: Lithofacies C is observed in a 50 cm thick exposure in the upper most part of the outcrop. Lithofacies C is formed by loose unsorted sediment of light grey color and appears to show horizontal stratification (Fig. 10A,B). Lithofacies C forms a scree that covers the lithified part of the outcrop.

Description of GPR facies C: GPR facies C is only recognized in the northern end of the outcrop perpendicular profiles. Its reflectors contrast clear to the geophysical character of GPR facies B and GPR facies A. GPR facies C displays horizontal, continuous reflectors. The abrupt
from a similar geological setting. The horizontal reflectors are interpreted as Quaternary talus slope or beach gravel deposits. Quaternary (Fig. 10 A-D). Furthermore, eastwards from the contact of facies B to the GPR profile 2 acquired 3 m behind the GPR facies C were not correlated to the outcrop, however, the interpretation of these horizontal reflectors against the chaotic GPR facies B indicates an onlapping relationship (Fig. 10F and Fig. 11B).

Interpretation of facies C: Lithofacies C and GPR facies C likely represent Quaternary talus slope or beach gravel deposits. Quaternary talus slope deposits as observed in the Fortet overview DOM (Fig. 5, A) are supported by GPR characteristics presented by Onaca et al. (2016) from a similar geological setting. The horizontal reflectors are interpreted to represent modern talus shedding events with periodically intense rockfalls, comprising of poorly sorted detritus of the exposed Wordiekammen Formation. The beach gravel deposits, on the other hand, are supported by episodes of relative sea-level drop due to isostatic rebound (Forman et al., 2004). Beach gravel sediments are often characterized by horizontal to sub-horizontal deposits (Neal et al., 2002; Nemec and Steel, 1984). The link between lithofacies C and GPR facies C is not straightforward and these two facies might therefore represent two different depositional environments. Both lithofacies C in the outcrop and GPR facies C are interpreted to represent recent Quaternary un lithified deposits.

5. Discussion
5.1. Dataset integration

The integration of the datasets allows to directly correlate outcrop features to GPR reflectors. GPR profile 2 was acquired 3 m behind the outcrop and therefore portrays nearly the same features as the outcrop (Fig. 10A-D). Furthermore, eastwards from the contact of facies B to facies A, the westward dipping carbonate benches of the Minkinfjellet Formation correlate with the westward dipping GPR reflectors (Fig. 10B, D). Tilted carbonate beds (facies A) have a sharp bedding dip-parallel boundary with the paleokarst breccias (facies B). The orientation of the boundary between facies B and facies A in the outcrop, the DOM and the GPR profiles is expressed consistently in all datasets (Fig. 9). This confirms that the paleo-cave base is observed in the outcrop and GPR survey. In addition, the chaotic paleokarst breccias in the outcrop correlate with chaotic diffracted GPR reflectors. The quaternary colluvial deposits of GPR facies C were not correlated to the outcrop, however, the overlap of the DOM demonstrates that this contact overlaps with a pronounced increase in steepness of the talus slope (Fig. 5A).

5.2. Breccia, extent and geometry

Displaying the interpretations of the GPR profiles together with the DOMs (Fig. 12B) suggests that facies B dominates the entire survey area. Conversely, facies A is restricted to the eastern areas of the survey site. Typically, the coherent sharp, dip-parallel transition from paleokarst breccias to undisturbed stratigraphy is one of the key characteristics of karst and paleokarst features in evaporitic karst systems, where it marks the paleo-cave floor (Simpson, 1988). In depositional terms, facies B represents the stratigraphic level of gypsum deposition which was later dissolved and replaced by the paleokarst breccias of lithofacies B, whereas the carbonates of facies A are relatively stable (Fig. 13; Eliassen and Talbot, 2005). Higher up in the stratigraphic succession at Wordiekammen, located 2 km to the north-east from the Rudmosepynten outcrop, the Wordiekammen Formation is intersected by cross-cutting paleokarst breccia pipes (Eliassen and Talbot, 2005; Nordeide, 2008; Wheeler et al., 2011). These are displayed as vertical 42.5 m wide and 105.5 m high pipes interpreted in the outcrop (Nordeide, 2008) and are shown as diffracted signals in GPR acquired on Wordiekammen by Wheeler et al. (2011). At Rudmosepynten we are able to show that the paleokarst breccia extends for more than 150 m beyond the outcrop and forms a connected paleo-cave system exceeding the area of 16 000 m² (Fig. 12A). This study suggests that the continuous paleo-cave system extends further under Wordiekammen (Fig. 12A) and is likely to be the underlying source determining the presence of the cross-cutting breccia pipes on the Wordiekammen Plateau. This is supported by the occurrence of undissolved gypsum further to the north, in the lateral position of the paleokarst breccias as suggested by Eliassen and Talbot (2005).

This study investigated breccia deposition immediately above the paleo-cave base. Expanding the area of investigation to other parts of the paleokarst succession may help to understand paleokarst depositional environments, irregular geometries and their extent beyond the outcrop. Dissolution collapse breccias are a targeted hydrocarbon reservoir in other Carboniferous rift sequences on the Barents Shelf (Savagoto et al., 2012). By understanding their geometry and scale in Svalbard we can better understand their potential offshore. This approach is not only relevant for paleokarst outcrops and analogues but can also be transferred to other petroleum systems such as karstified carbonates (Fernandes et al., 2015) and other limestone reservoirs (Martinez et al., 1998).

5.3. Method assessment

This study shows that the integration of DOMs with GPR profiles has the potential of directly linking GPR reflection patterns to outcrop equivalents. Ensuring that the GPR is portraying the nearly vertical outcrop, it has to be followed by a surface suitable for GPR acquisition. Moreover, the resolution of the DOM and GPR limit the interpretation and linkage exemplified in the portraying of carbonate beds. All datasets need a surface or feature that can without doubt be correlated across the datasets. The westward dipping carbonate layers of facies A offer a good opportunity to quantify the differences in vertical resolution between each method. In the outcrop we identified more than 60 carbonate beds. In contrast, only a total of 49 carbonate beds can be identified from the DOM. With the relationship of the vertical resolution being one quarter of the GPR wavelength for this study the vertical resolution is 0.6 m, resulting in the imaging of 19 tilted reflectors. This comparison shows that both the DOM and GPR are not able to resolve the details of outcrop in full, thus emphasizing the necessity of obtaining detailed data from conventional fieldwork to compliment and ground truth model interpretations. Future efforts could include vertical radar profiling to compare GPR reflection characteristics with lithology (Pringle et al., 2009).

It is important to stress that both the DOM and GPR datasets rely on a good description of the outcrop. The direct correlation in more complex geological environments also requires good knowledge about subsurface geophysical parameters for a precise illustration of the subsurface. This method allows us to increase the certainty of digital and geophysical interpretations. In a future step the direct correlation of the datasets into
the subsurface behind the outcrop allows us to build 3D geo-models of paleokarst features and potentially other sedimentary structures/features observed in the outcrop, DOM and GPR. For future efforts this method could be integrated with electrical resistivity tomography and shallow seismic across a large plateau to provide more geophysical characteristics.

With this study we have shown that the integration of detailed outcrop descriptions, DOMs and GPR directly on top of the outcrop yields the potential of a geologically driven interpretation of the DOM and GPR data. This geologically driven interpretation improves the confidence in the interpretations and the 2D GPR profiles enable us to extend our observations into the third dimension.

Carbonates and in particular karstified carbonates comprise large three-dimensional heterogeneities and are difficult to model into the subsurface behind outcrops. The link of geophysical data with outcrop data enables a better 3D geomodelling of these environments by adding about internal architecture, dimensions and composition information beyond the outcrop.

6. Conclusion

In this contribution we have integrated shallow subsurface ground penetrating radar (GPR) data with conventional outcrop data and digital outcrop models (DOMs). By integrating these datasets, we were able to directly and indirectly link lithofacies characteristics to GPR facies reflectors. We were also able to correlate key horizons in outcrop, DOM and GPR to produce a three-dimensional geology-driven interpretation of geophysical data. This has enabled us to demonstrate a clear link between the chaotic nature of paleokarst breccias in outcrop and the highly diffracted GPR reflectors of the equivalent GPR facies. In the GPR profiles we could trace the paleokarst breccia and the paleo-cave base for 150 m beyond the outcrop. In this study we have shown that the integration of outcrop, DOM and GPR data sets have the potential to strengthen and extend the interpretation of conventional outcrop data.
None the less detailed outcrop descriptions are essential to improve the interpretation of both DOM and GPR datasets.

CRediT author statement

**Julian Janocha:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Fieldwork, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. **Aleksandra Smyrak-Sikora:** Validation, Visualization, Writing – review & editing. **Kim Senger:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. **Thomas Birchall:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Agisoft, 2020. Agisoft Metashape Professional (Version 1.6.2) (Software). https://www.agisoft.com/downloads/metashape.

Ahlborg, A., Stenmerik, L., 2015. Depositional evolution of the Upper Carboniferous – Lower Permian Wordiekammen carbonate platform, Nordfjorden High, central Spitsbergen, Arctic Norway. Norw. J. Geol. 95 (1), 91–126. https://doi.org/10.17850/njg95-1-05.

Anderson, R.Y., Kierzké, K.K., Rhodes, D.J., 1978. Development of dissolution breccias, northern Delaware Basin. In: New Mexico and Texas, vol. 159. New Mexico Bureau Mines & Mineral Resources.

Aasruot, U., Aignier, T., 1999. Towards realistic aquifer models: three-dimensional georadar surveys of Quaternary gravel deltas (Singen Basin, SW Germany). Sediment. Geol. 129, 281–297. https://doi.org/10.1016/S0037-0738(99)00068-8.

Bælum, K., Braathen, A., 2012. Along-strike changes in fault array and rift basin geometry of the Carboniferous Billefjorden Trough, Svalbard, Norway. Tectonophysics 546–547, 38–55. https://doi.org/10.1016/j.tecto.2012.04.009.

Bellian, J.A., Kerans, C., Jenette, D.C., 2005. Digital outcrop models: applications of terrestrial scanning lidar technology in stratigraphic modeling. J. Sediment. Res. 75, 166–176. https://doi.org/10.2110/jsr.2005.012.

Bemis, S.P., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S.T., Bangash, H.A., 2014. Ground-based and UAV-Based photogrammetry: a multi-scale, high-resolution mapping tool for structural geology and paleoseismology. J. Struct. Geol. 69, 163–178. https://doi.org/10.1016/j.jsg.2014.10.007.

Bergh, S.G., Braathen Jr., A., Maher, H.D., 2000. Tertiary divergent thrust directions from partitioned transpression, Breggerhvaluya, Spitsbergen. Norw. J. Geol. 80 (2), 63–81.

Blatnik, M., Culver, D.C., Gabrovsek, F., Knez, M., Kogovsek, B., Kogovsek, J., Liu, H., Mayaud, C., Mihove, A., Mulec, J., Najarov-Aljanic, M., Otanicar, B., Petric, M., Pipan, T., Prelovsek, M., Radvac, L., Shaw, T., Slabe, T., Sebela, S., Zupan Hajna, N., 2020. Late cretaeous and Paleogene paleokarsts of the northern sector of the Adriatic carbonate platform. In: Knez, M., Otanicar, B., Petric, M., Pipan, T., Slabe, T., Blatnik, M., Culver, D.C., Gabrovsek, F., Kogovsek, B., Kogovsek, J., Liu, H., Mayaud, C., Mihove, A., Mulec, J., Najarov-Aljanic, M., Prelovsek, M., Radvac, L., Shaw, T., Sebela, S., Zupan Hajna, N. (Eds.), Karstology in the Classical Karst. Springer, Cham, pp. 11–31.

Blount, D.N., Moore Jr., C.H., 1969. Depositional and non-depositional carbonate breccias, chiantilla quadrangle, Guatemala. Geol. Soc. Am. Bull. 80 (3), 429–442. https://doi.org/10.1130/0016-7606(1969)80[429:DCBCTW]2.0.CO;2.

Braathen, A., Bælum, K., Maher, H., 2014. Growth of extensional faults and folds during deposition of an evaporite-dominated half-graben basin; the Carboniferous Billefjorden Trough. Svalbard. Norwegian Journal of Geology 91 (3), 157–161.

Braathen, A., Bergh, S.G., Maher, H.D., 1999. Application of a critical wedge taper model to the tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard. Geol. Soc. Am. Bull. 111 (10), 1486–1485. https://doi.org/10.1130/0016-7606(1999)111[1486:ACWTTM]2.0.CO;2.

Bubeck, A., Velemirova, E.A., Jones, R.R., Wilkinson, M.W., 2011. Combining GPR and terrestrial LiDAR to produce 3D virtual outcrop models. In: Near Surface 2011 - 17th EAGE European Meeting of Environmental and Engineering Geophysics. Near
