Use of drones to analyse sedimentary successions exposed in the foreshore

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**Abstract:** Drones have revolutionised the gathering of geoenvironmental data over the last decade. To date, the majority of drone studies of sedimentary rock successions have focussed on well-exposed vertical to subvertical cliff sections. Here, we describe a fundamental method to obtain new data and perspectives on sedimentary successions exposed in partially-obscured foreshore or other horizontal to subhorizontal outcrop surfaces using drones. We illustrate the technique using an example from foreshore exposures of Jurassic strata near Helmsdale, Scotland, UK. Our method aims to make the process of safely collecting drone footage accessible and covers practical considerations from pre-field preparation to data processing. Capturing drone imagery in a foreshore setting involves trade-offs between the time of day which constrains the lighting, the time of year which determines algal cover and tidal range, and the flight time available which indirectly governs image resolution. We show how: (1) orthomosaic images can be used to view sedimentary deposits at different scales and angles enabling identification of large-scale sedimentary features marked by small-scale changes in orientation and lateral variability; (2) production of digital elevation models permits differentially weathered features covered by water or algae to be distinguished, and (3) drones can be used for close up photography of inaccessible features.

**Keywords:** foreshore, drone, UAV, UAS, sedimentary deposits, NE Scotland

1. **Introduction**

Drones have revolutionised the gathering of geoenvironmental data in the last decade because they allow the collection of large amounts of high-resolution, spatially continuous and georeferenced data (*e.g.*, Madjid et al., 2018; Dering et al., 2019; Wakeford et al., 2019). Furthermore, data collection is relatively quick, low cost and drones can be used in inaccessible areas (Jordan, 2015). Drones have been commonly referred to as Unmanned (i.e. remotely piloted) Aerial Vehicles (UAVs), with the term Unmanned Aircraft Systems (UAS) encompassing the aircraft, control systems and payload, *e.g.*, survey equipment. Surveying payloads can include cameras, sensors and light-weight LiDAR equipment which have allowed drone to be used for a wide-range of purposes including atmospheric investigations (*e.g.*, Thomas et al., 2011, Brownlow et al., 2016, Wilcox et al., 2016), ecology (*e.g.*, Gonzales et al., 2016), agriculture (*e.g.*, Bendig et al., 2014), viticulture (*e.g.*, Matese and Di Gennaro, 2018), forestry (*e.g.*, Wallace et al., 2012), glaciology (*e.g.*, Immerzeel et al., 2014), assessing glacial geomorphology (*e.g.*, Ely et al., 2017), river systems (*e.g.*,...
Lejot et al., 2007; Flener et al., 2013) and coastal erosion (e.g., Turner et al., 2016). Often, the outputs of such surveys include individual high-resolution aerial images and photogrammetric products such as orthomosaic images, georeferenced data maps and 3D digital models (Bemis et al., 2014; Pavlis and Mason, 2017; Buckley et al., 2019; Nesbit et al., 2020). The latter has been considerably refined in the last few years by the availability of structure-from-motion (SfM) based processing tools (Turner et al., 2012; Westoby et al., 2012; Carrivick et al., 2013; Eltner et al., 2016; Woodget et al., 2017) which automatically match features in multiple overlapping 2D images and simultaneously determine the moving camera position to construct a 3D model (Micheletti et al., 2015).

The widespread application of drone technology to geological problems initially lagged behind their use in solving environmental issues because, on the tens of metres to kilometres scale, many geologists are inherently more interested in the 3D analysis of rock bodies and structures (Bilmes et al., 2019), rather than 2D aerial surveys. This is in contrast to environmental studies, such as monitoring animal movements or the spatial extent of vegetation, where the remote 2D information is invaluable. Instead, to obtain accurate, high-resolution 3D models of outcrops geologists adopted both terrestrial and piloted aircraft-based LiDAR surveys from close to the outset of their availability, despite their high cost (McCaffrey et al., 2005; Buckley et al., 2008a, 2008b). Only with the advent of SfM photogrammetry alongside advances in digital cameras and computer processing tools have geologists embraced the use of drones. This is because drone-SfM outputs can be of comparable quality, and in some cases preferable; in addition, the equipment, data collection and processing required is simple and much lower cost compared with LiDAR surveys (Westoby et al., 2012; Buckley et al., 2017; Cawood et al., 2017; Dering et al., 2019). The advent of SfM has also made the acquisition of high-resolution topographic imagery for mapping on the kilometre-scale both accessible and affordable in a way that LiDAR was not (Pavlis and Mason, 2017; Chesley and Leier, 2018; Madjid et al., 2018).

Drones have proved particularly useful for surveying geological locations that are dangerous to access. For instance, in the quarrying industry, drone surveys combined with land-based techniques are used to aid detailed mapping of joint planes and remote assessment of heavily fractured vertical rock faces, informing extraction and safety planning (Wilkinson, 2017; Salvini et al., 2017). In academia, drones have been used to monitor volcanic plumes (e.g., Shinohara, 2013; Mori et al., 2016; Schellenberg et al., 2019) and other geohazards (e.g., Niethammer et al. 2012), and Wakeford
et al. 2019 combined infrared and visual data to produce a 3D thermal outcrop model of an active volcano. High-resolution spatial coverage of field locations that are difficult to access has been obtained using drones. For instance, Piras et al. (2017) developed a UAV-based workflow for producing slope and aspect maps in mountainous terrain and McFarlane et al. (2013) used drone imagery inside caves for karst research. In particular, UAVs have been used to address structural problems (e.g., Bemis et al., 2014; Johnson et al., 2014; Vasuki et al., 2014; Angster et al., 2016; Vollgger and Cruden, 2016; Bi et al., 2017, Cawood et al., 2017, Gao et al., 2017; Ko and Lee, 2019) and to examine fracture networks in exposures used as analogues for hydrocarbon reservoirs (e.g., Bond et al., 2015; Faÿ-Gomord et al., 2017).

Similarly, drone-SfM technology is transforming data gathering for stratigraphical and sedimentological research. In some cases, this is building upon extensive earlier work that utilised terrestrial and helicopter LiDAR surveys together with ground and aeroplane-based photographs to construct virtual outcrop models or maps (e.g., Enge and Howell, 2010; Hampson et al., 2012; Eide et al., 2014; Pires et al., 2016; Pitts et al., 2017). The majority of sedimentological studies to date have concentrated on vertical or steeply inclined exposures (e.g., Hampson et al., 2012, Pierce et al., 2016, Chesley et al., 2017; Pitts et al., 2017; Priddy et al., 2019; Korus et al., 2020). However, a few studies have aerially-mapped sedimentological features on the kilometre-scale (e.g., Chesley and Leier, 2018), and Nieminski and Graham (2017) examined the stratigraphical architecture of very well-exposed, laterally continuous and fairly uniformly dipping strata in a wave-cut platform. Most sedimentological studies to date, have been in locations with little or no vegetation, such as arid regions (Pierce et al., 2016; Hansman and Ring, 2019), glacially scoured areas (Buckley et al., 2010; Nesbit et al., 2018) and extensive well-exposed vertical cliffs (Eide et al., 2015; Muhlbauer et al., 2020). As illustrated by many of the studies cited above, a key advantage of the use of drones for sedimentological and stratigraphic studies is that the large-scale view can be used to detect subtle changes in geometry and lateral variation that are a common characteristic of sedimentary successions.

1.1. UK Legislative Framework

The flying of drones, no matter what the size, requires that the up-to-date safety and legislative details are met (Cunliffe et al., 2017; Peacock and Corke, 2020). For instance, at the time of this survey in 2018, without additional permissions, UK Civil Aviation Authority (CAA) regulations for the use of sub-7 kg drones prevented them from being flown: above 120 m (400 ft) above ground level;
beyond a maximum horizontal distance of 500 m; and within 150 m of crowds or built up areas or within 50 m of property or members of the public not under the control of the pilot (30 m during take-off/landing).

Up-to-date information on regulations for the UK can be found in CAP 722 (current version Civil Aviation Authority, 2020), which provides information on how to operate in accordance with articles relevant to Unmanned Aerial Systems (UAS) in the Air Navigation Act 2016 and amendments (reproduced as CAP 393, Civil Aviation Authority 2016). From December 2019 the UK CAA required a pilot test and registration to fly a craft over 250 g in any circumstances (refer to CAA website for updates https://register-drones.caa.co.uk); additional regulations apply if the drone is being used for surveillance (i.e. fitted with a camera – see Article 95 of Air Navigation Order 2016) to protect people’s personal privacy. Restrictions on the use of drones vary by country and legislation is regularly advancing to ensure safety, privacy and protection of wildlife.

1.2. Scope of this study
In this study, we present a step by-step accessible method for recording extensive areas using data from drones and, for the first time, show how that can be applied to partially obscured foreshore. Similar to previous studies on well-exposed vertical cliffs, we show how drone data is a key tool for characterising the depositional geometry of sedimentary deposits in horizontal to subhorizontal outcrops. We document best practice and highlight practical considerations for foreshore areas together with demonstrating how drone-acquired imagery can assist in the recording and interpretation of sedimentary deposits obscured by algae or water. Our method also outlines, particularly for new users of this technology, considerations for planning and data processing. The aim of our study, given the increased interest in using drones to capture more data, is to show readers what can easily be achieved on a non-commercial basis, rather than providing a method for high-accuracy models of the environment (for such detail see Woodget et al., 2015; Eltner et al., 2016; Vollgger and Cruden, 2016; James et al., 2017; Riley and Wilkinson, 2018; Tmúsić et al., 2020). Our findings are based on a survey of the foreshore near Helmsdale in NE Scotland, UK. We have used this survey to provide examples to illustrate: image resolution, identification of large-scale sedimentary structures and features, correlation to a sedimentary graphic log, the value of using a digital elevation model, oblique images viewable within the landscape in Google Earth or in an interactive 3D model, and close-up photography of inaccessible areas. Many aspects of the
method are directly applicable to horizontal and subhorizontal outcrops of sedimentary rocks that are variably exposed.

2. Field setting of the examples used to illustrate the method

The method is illustrated using examples from c. 5 km length of rocky foreshore section near Helmsdale, NE Scotland, UK ([ND 004 128 to ND 042 159]; Fig. 1). This location presents all the access and operational challenges commonly found in rocky foreshores including tidal restrictions, uneven topography, rock pools, cobble cover, algae, wildlife, sea fog, shadows cast by cliffs and hills, infrastructure, nearby habitation and human activity.

Fig. 1. Location of the section near Helmsdale, NE Scotland [ND 028 153], including infrastructure and the place names of the locations described. MHWS and MLWS: Mean high- and low-water mark spring tides respectively. Inset: Map of England, Scotland and Wales with a red box showing the location of Helmsdale.

2.1. Geological and natural physical setting

The foreshore near Helmsdale is 30–100 m wide and exposes a Jurassic succession of interbedded cobble- to boulder-sized breccias, sandstones and mudstones with complex depositional
geometries. The beds generally dip between 5–30° to the north-east and are gently folded. The foreshore is adjacent to a narrow (50–400 m) strip of flat land, landward of which the ground-level rises steeply to an elevation of 400–500 m. Over most of the area this abrupt change in topography is coincident with the line of the Brora-Helmsdale Fault, which runs near-parallel with the coast and brings the Helmsdale granite in the footwall adjacent to the Jurassic succession.

The Jurassic breccias comprise units that are typically 0.5–2 m thick and form reefs that stand up to several metres topographically proud of the finer-grained sandstones and mudstones that mostly lie at foreshore level (Figs. 2a and 2b). The clasts are mostly composed of reworked Devonian and Jurassic deposits. The exposures of the breccia beds, and to a lesser degree the sandstones, are commonly discontinuous over a few or tens of metres. This can be due to syn-sedimentary faults, or depositional geometry, or post-deposition structural movement, or more recent erosion. Over most of the section, there is substantial cover by marine algae throughout the seasons, which has increased in density and extent in recent years. This increase in algae has been noted to an even greater extent in other parts of the world, for instance the recent bloom of Sargassum (Wang et al., 2019). The fine-grained, and therefore low lying, beds in the foreshore are also often obscured by beach-cobbles and -sand that are shifted daily by coastal processes.

The tidal range is 2–4 m and the exposures are almost completely submerged at high tide, leaving a window of just a few hours each day when they can be observed. The upper few metres of the foreshore and the backshore comprise one or more storm berms composed of cobbles.

2.2. Infrastructure, human activity and animals

The A9 trunk road follows the Helmsdale coastline about 20–400 m from the high-water mark, and a single-track railway line runs immediately seaward of the road along 3 km of the section (Fig. 1). The fields either side of the railway and road are used for grazing. The road crosses the outflow of the Helmsdale River via a high bridge just inland of the Helmsdale village harbour. Within the study area, in addition to Helmsdale village, there are five occupied dwellings located above the storm berm, each less than 40 m from the high-water mark. The area is well known for its high abundance of birdlife and sea mammals. There is regular civilian activity on the foreshore, in the coastal waters and in the air and whilst the activity is daily, this is not a densely populated or well visited area. The infrastructure, human and animal activity all present collision hazards for UAVs and were mitigated
for in the Risk Assessment and Method Statement (commonly referred to as RAMS; see Method for more details) to avoid distressing animals and to comply with CAA regulations.

Fig. 2. A relatively well-exposed area (a) and a relatively poorly-exposed area (b) of foreshore near Helmsdale; (c) the DJI Mavic Pro drone on a launch pad showing its small size; (d) the larger DJI Inspire 1 drone being brought in to land; (e) ground control location point marked by a frisbee with tape marking the centre.

3. Method

3.1. Equipment

Both fixed-wing and multi-rotor UAVs are commonly used for scientific surveys. Fixed-wing drones have longer flight times and typically have greater ground speed, however, their reduced mobility leads to them being better suited to linear flights. They also require permission for an extended visual line of site (EVLOS) of at least 1 km and a suitable runway area. A further consideration is that fixed wing drones generally need to fly at higher elevation than a multi-rotor because of air turbulence near the ground, leading to a trade off with image resolution. The shorter flight time of multi-rotor drones is compensated for by the benefits of vertical take-off and landing and greater manoeuvrability, stability and control (Jordan, 2015), making these types of UAVs particularly well-suited to detailed surveys of relatively small areas, with limited launch and landing space; all of which are typical of many geological field areas. The smaller multi-rotor drones are designed to be easy to transport, which is particularly useful if pedestrian access to the survey site is challenging.
Their ability to hover at low level is useful for close-up photography. A more detailed review of points to consider when selecting drone equipment is provided by Dering et al. (2019).

The UAVs selected for our survey were multi-rotor professional drones. They were two DJI Mavic Pro small drones (Fig. 2c), and one DJI Inspire 1 (Fig. 2d); both are classed as small unmanned aircraft by UK Civil Aviation Authority (CAA) definitions. Both models are quad-rotor aircraft suitable for the vertical take-off and landing required from the cobble foreshore or uneven backshore where suitable small launch areas (such as concrete drain covers, or areas of hardstanding) could be identified (Figs. 2c and 2d). The drones both have a range of intelligent flight mode options, for example, allowing the UAV to hover precisely, avoid obstacles, follow pre-set flight patterns and take-off and land automatically. They are each operated from a remote-control unit to which a tablet or smartphone can be connected, allowing the pilot to monitor the camera images during flight.

The DJI Mavic Pro is a compact, light-weight vehicle, designed to be portable, with a folding platform, inbuilt 4K camera and detachable rotor blades. Its small size means that it cannot carry additional equipment. Its light weight also makes it more susceptible to unexpected gusts of wind and less robust.

The DJI Inspire is a larger platform designed for professional film-making and in this case was used with a Zenmuse 4K camera. A polarising lens can easily be added to the camera, thereby enabling it to image some features below shallow water in the shoreface. The Inspire is able to support two remote control units so that the camera and drone can be operated separately by two people if required. Its large size means it is heavy and bulky to carry to field locations and relatively expensive to replace or repair if damaged.

Weather conditions are a significant factor when planning and deciding on flying drones as rotary wing drones have lower tolerances than fixed wing drones. For small rotary wing drones, even moderate wind speeds of 8 m s\(^{-1}\) can shorten the flight time and reduce pilot control via increased motor demands on the battery; in extreme conditions the motors can overheat and shut down. Poorly considered wind effects, including changes with altitude and topography increase the chances of hitting obstacles or being damaged beyond recovery (Jordan, 2015) or risking injury to the team particularly during take-off and landing. The Mavic and Inspire can fly for 21 and 18 minutes respectively on one battery (see Table 1). In both cases, weather conditions need to be dry.
with good visibility and wind speeds of less than 5 m s⁻¹. As battery usage is intensive, additional batteries were carried to ensure the drone could be operational throughout the low tide window and unexpected weather conditions. These lithium ion polymer batteries represent a fire risk and require careful handling and charging, and storage in appropriate fire-safety bags when not in use (NERC, 2016).

Table 1. Drone specifications

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>DJI</th>
<th>DJI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Mavic Pro</td>
<td>Inspire 1</td>
</tr>
<tr>
<td>Maximum take-off weight (including payload)</td>
<td>743 g</td>
<td>3.5 kg</td>
</tr>
<tr>
<td>Propulsion</td>
<td>4 x DC electric motors</td>
<td>4 x DC electric motors</td>
</tr>
<tr>
<td>Speed (max)</td>
<td>40 mph / 35 knots</td>
<td>49 mph / 43 knots</td>
</tr>
<tr>
<td>Endurance</td>
<td>21 minutes</td>
<td>18 minutes</td>
</tr>
<tr>
<td>Transmitter range</td>
<td>4 km</td>
<td>3.5 km</td>
</tr>
<tr>
<td>Sensors</td>
<td>4K camera</td>
<td>Zenmuse 4K camera</td>
</tr>
</tbody>
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3.2. Flight planning

Flights were planned by experienced drone pilots and in accordance with the University of Birmingham’s flight operations manual (University of Birmingham, 2018) which covers the items listed in CAP722 (Civil Aviation Authority 2020); site specific considerations were included in the RAMS (see ‘Risk Assessment and Method Statement’ below) and insurance was arranged.

Prior to fieldwork, the physical setting and the objectives of the campaign were discussed and the exact area to be covered was identified. Sedimentary logging of the 5 km foreshore had been completed during a previous field season. The graphic logging was completed in five sections each covering foreshore of c. 1 km in length, and each with at least one good access point. This division also proved suitable for the daily drone work because these c. 1 km sections could be recorded in one day taking into account the tides and daylight hours. The sections were placed in priority order, in case bad weather or other unexpected events cut short the field campaign. We identified the easiest and closest access point for each section, to avoid carrying kit for long distances and in case of an emergency. The planning also took account of the most likely locations where the public may access the beach, and therefore the number of field assistants required so that we could ensure their safety and avoid unexpectedly filming people (see Section 3.4).
The Mavic is just 0.34 m wide and because it is so small, unless visibility was exceptional, was only flown up to 250 m away from the pilot. Hence, the daily c. 1 km sections were subdivided further into flight segments, requiring one or two relocations of the pilot along the beach in the course of the day. Flights were planned using DJI Ground Station Pro and DroneDeploy software, which provides a Google Earth satellite image on which a polygon of the flight area can be drawn (Fig. 3). Given the variables of the area, altitude, desired velocity, frontlap and sidelap, the programme plans the number of flight lines and image captures, and estimates the flight time and battery requirements under optimal weather conditions. The software has the advantage of flight automation and easy adjustments to flight plans in the field if conditions change. It can also be overridden by manual control at any point during the flight.

A flight altitude of 50 m was used. This altitude gave an image resolution of 1.6 pixel/cm at the surface and enabled easy identification of features of 0.1 m or greater. Overlapping flight lines were planned with 65% sidelap and 75% frontlap, which are well within range to allow good photogrammetric reconstruction (Tmůsić et al., 2020) whilst ensuring that the volume of data to be collected, within the time available, was manageable.

3.2.1. Airspace and access permission

Access to the airspace was checked with the relevant airspace control, in this case National Air Traffic Services (NATS). The Helmsdale area is within military Low Flying Area 14(T) and the
aeronautical charts indicated the north-western edge of danger area EDG703 (TAIN) is located a minimum of 1.5 km to the south east of the planned survey zone. The RAF-published timetables for military use of low flying areas were used to schedule drone survey flights. In addition, to ensure deconfliction of aircraft entering and exiting EDG703, RAF Tain airbase was contacted at the start and end of each flying day. Although recreational and commercial aircraft are not routinely expected below 150 m (500 ft) in the survey zone, Notice to Airmen (NOTAMs) were checked daily.

Permission from all landowners along the full length of the foreshore was obtained in writing prior to the commencement of operations. Control of persons and properties within 30 m of the take-off zone was agreed during flight operations with residents in the five dwellings seaward of the road and railway line. In addition to maintaining permitted separation distances, flying was avoided in the vicinity of the railway line within 30 minutes of timetabled trains (typically 10 per day).

3.2.2. Risk Assessment and Method Statement

A Risk Assessment and Method Statement (RAMS) was prepared covering the site-specific details, equipment, objectives, flight operations, air space co-ordination, ecological considerations (mainly bird presence), safety, project team roles, emergency contacts, pre-flight checklist and data protection (Fig.4). The method statement planned for one pilot, one reserve pilot / field assistant and two further field assistants to work together in one section to ensure all access points were covered and to deal with any issues including hazards in the airspace. A fourth assistant at the residential base was also available in case of emergencies.

3.2.3. Timing

Late spring was chosen for our survey as the most likely time for calm, dry weather, low algal cover prior to summer blooms and having a significant amount of daylight for the latitude. A period of spring tides was chosen, maximising exposure of the foreshore outcrop. Low tides were in the early morning and early evening. Early morning images had shadow on the steeper (west to south-west facing) exposure faces of the breccia beds, but evening flight times were cut short by the Sun dipping behind the hills hours before sunset (see ‘Geological and natural physical setting’; Fig. 1) so morning flights were prioritised. Extra field days, beyond the number needed for the flight plans were provisionally included in case of time lost to inclement weather or other challenges.
Fig. 4. A best-practice workflow for obtaining UAV-based imagery on the foreshore, from initial planning to flight operations. Key stages are shown in boxes outlined in a thick purple line. Trade off decisions 1 to 4 relate to foreshore and other tidally influenced settings and are explained fully in the discussion. ATC = Air traffic control; NOTAMs = Notice to Airmen. Note that the Pre-flight checklist is not exhaustive.
3.3. Drone fieldwork daily routine

For repeated, successful flights, flight operations were led by checklists (Fig. 4). The current weather, forecast, site conditions, and NOTAMs were checked at the start of the day. Immediately prior to the day’s flight the team was briefed, the physical and mechanical integrity of all drone and communication equipment was checked, and the kit checklist was used to ensure nothing that was required was left at the field base. This was followed by communication with Tain RAF base. On site, good or adequate take-off and landing sites were identified for each flight section, and eight brightly-coloured 0.3 m diameter ground control points (frisbees) with their centres marked were placed, roughly evenly spaced, along the beach within the flight area (Fig. 2e). The location of each of these was carefully recorded using hand-held Global Positioning System (GPS) to enable georeferencing of composite images produced after the field campaign. Overall model georeferencing accuracy can be enhanced by using high-precision differential GPS / Global Navigation Satellite System (GNSS), Real Time Kinematic (RTK) GPS / GNSS or total station systems, although they are comparatively expensive (McCaffrey et al., 2005, table 2; Wilkinson, 2014). Immediately prior to flying the airspace was visually checked.

During flights, the pilot maintained unaided visual contact with the drone, and took manual control if required. Radio contact was maintained with field assistants at all times in case of people entering the flight area or any other activity in the airspace (aircraft, boats and wildlife (especially birds)). In the case of persons entering the flight area, assistants asked if they would be willing to wait until the end of the survey for their own safety; if they were not willing to wait the pilot was informed so that the drone could be landed. Automated flight paths were paused and the batteries changed when ~40% battery power was remaining; this enables flights to be more conservative, reducing risk. At the end of each flight window period RAF Tain was contacted. After flying, flight logs were examined and the group debriefed to discuss successes and issues (Fig. 4).

3.4. Image processing

At the end of each day, the data was downloaded and back-ups were made to several high capacity storage places. The images were grouped to match the five originally defined, logged sections. After the field campaign, these batches of data were processed using Agisoft PhotoScan Pro v. 1.4.2 software (Note: the current version is called Metashape) to produce an orthomosaic photograph and digital elevation model (DEM) of each section, using structure-from-motion (SfM) photogrammetry methods (Bemis et al. 2014). Woodget et al. (2015) provide a comprehensive
account of photogrammetric processing, which we largely follow here, except to save processing time we georeferenced the model with ground control points (GCPs) identified on the photographic images following the sparse point cloud build (rather than on a textured model), as outlined briefly below.

An image dataset batch was input to the software and blurred images or unwanted sections of images (such as those showing property or people) were removed manually. This ensures privacy, cleans data and reduces point matching problems with the SfM algorithm. Agisoft PhotoScan was used to align the images by identifying matching points on overlapping photographs, generating a sparse point cloud. This cloud was then registered to OSGB36 datum (the British National Grid coordinate system) by first inputting the positional coordinates of the GCPs, and then by the software optimising the estimates of the camera and sparse point cloud positions around the GCP locations. Next, a dense point cloud was produced using a multi-view stereo-reconstruction of the pixel values of the re-aligned images, followed by construction of a mesh, or continuous surface between the dense cloud points. The software allows dense cloud processing at five different levels of resolution, with ultrahigh being the most computationally intensive, and the lowest being suited for rapid checks. We found the ‘high’ setting (one below the highest), was optimal for this survey, giving the best balance of DEM resolution (derived from the point cloud), processing times on the available computing resources, and post-processing usability of the models. The survey data was exported in multiple formats, including 2D georeferenced orthomosaic and DEM TIFFs, and a textured KMZ file. The geotiffs can be viewed in a GIS programme such as ArcGIS or QGIS. The DEM images can then have the ‘hill shading’ option applied to highlight the relief of the beds.

4. Results

The drone survey was carried out in mid-May 2018 over a period of three consecutive days during some of the lowest tides of the year (mean low water 0.29–0.36 m). Low tide was between 06:49 and 08:17 hours, so the Sun was relatively low in the sky during the surveys creating shadows but advantageously, also enhancing definition on surfaces not entirely in the shade. Unusually for the area, weather conditions were calm, dry and clear throughout the field campaign, with winds of < 3 m s⁻¹ (0–2 on Beaufort Scale) making it perfect for drone work. As planned, drone imagery was captured along the 5 km of coast in a 200 m wide strip (i.e. c. 1 km² in total), from the backshore storm berm to the reefs of boulder beds below mean low spring tide.
During this campaign we collected >6500 static images. After returning from the field, we typically used around 1000, 5–6 MB images to generate a c. 4 GB orthophoto (TIFF image) of each c. 1 km long section of foreshore. The number of images collected would have been considerably greater if we had flown the drone at a lower elevation, to obtain higher resolution. Handling photogrammetry on this scale took days to process on a powerful computer. As such we suggest a minimum of an intel i9 processor, a graphics card from the recent Quadro NVIDIA RTX 2000 series and 64 GB RAM (256 GB RAM is recommended by Wilkinson, 2017) for the processing. To view and interrogate files of this size in a GIS programme, we used a computer with 32GB RAM and a high-quality gaming graphics card (e.g. EVGA GeForce GTX 1050 Ti GAMING, 4GB GDDR5, DX12 OSD Support (PXOC) Graphics Card 04G-P4-6251-KR). The photogrammetry files were held on the computer or a linked hard drive (rather than on a server, which slowed down access). The following examples of the photogrammetry and photographic outputs indicate the range of data obtained and how it can be used in a sedimentological context.

4.1. Image resolution

Figure 5 shows the aerial photography available from Ordnance Survey MasterMap (Fig. 5a), compared to the image resolution obtained for a 31 x 29 m area from the drones (Fig. 4b; 1.6 cm per pixel). The Ordnance Survey photographs were taken from a small aircraft flying at 1500 m and provide a resolution of 25 cm per pixel; this was the best aerial imagery of the area available prior to our drone survey. Figure 5b shows how the definition of the drone image allows the beach cobbles to be distinguished from more resistant (sandstone) beds, and the higher relief sandstones

![Fig. 5. Comparison of the colour and pixel resolution for two aerial imagery datasets for the area shown by the orange rectangle in Figure 6. (a) OS MasterMap image 2016 of an area 31 x 29 m, 1 pixel = 25 cm; (b) drone orthoimage from this study of exactly the same area as (a), 1 pixel = 1.6 cm, and (c) image showing the resolution at which the drone imagery starts to pixelate (width = 2.5 m).](image-url)
from the lower-relief mudstone beds. Both the colour and the definition enable the seaweed covered areas to be identified in the drone images. A small fault can also be seen running from the bottom left to upper right corners of both images with a lateral offset of up to 4 m. The magnification at which the drone images start to pixelate is shown in Fig. 5c.

4.2. Large-scale and inaccessible features

The aerial vantage point of the drone imagery both enabled the identification and assisted with defining the geometry of large-scale structural and sedimentological features. For instance, continuous and lensoid breccia beds (Figure 6b). Large-scale folding is indicated by a change in strike from the bottom to the top of Figure 6, highlighted by the dashed green lines. Although the change in strike could be identified by field mapping, the change is not that obvious in the field, but is visible immediately on the orthomosaics. Additionally, the orthomosaics provided information on features close to low water mark that are inaccessible on foot or only accessible for a very short period of low spring tides, such as the right-hand side of the features marked in red on Figure 6b.

![Fig. 6.](image)

4.3. Integration with field log

The sedimentary succession at Helmsdale is complex with lateral and vertical facies variability (Fig. 7a). The upper quarter of Figure 7b shows downcutting on the metre-scale and interdigitation of the breccia beds that is difficult to observe and record in the field. All of this data was used to enhance the field observations and to produce the graphic log (Fig. 7a).
Fig. 7. Comparison of field log (a) and drone imagery (b) from the same 400 m section of the foreshore near Gartymore, Helmsdale. Note that the clasts in the breccia beds are drawn to scale. The finer-grained deposits are divided according to their percentage sand. There is vertical exaggeration of the shape of the breccia beds.

4.4. Digital elevation models

Digital elevation models (DEMs), specifically digital surface models (see Section 5.2), produced from the photogrammetry were used to identify the outline of features with a raised or depressed relief, without the colour noise introduced on the orthomosaic photographs by the extensive algal cover. For example, one DEM (Fig. 8b) from our study area clearly shows a large (12 x 9 m) block embedded in stacked breccia beds, whereas it is only faintly visible on the orthomosaic image because it is partially obscured by algae (Fig. 8a) and was completely undetectable in the field at the time of the survey. Many of the clasts in the breccia beds, including this block, are composed of the distinct thinly-beded lithologies of the Caithness Flagstone Group (Devonian); this change in lithological character and the discordant orientation of the bedding enable the clast to be discerned on the DEM. The capacity of DEMs to highlight subtle changes in elevation was also observed by Kasprzak et al., 2018 in the identification of micro-relief on granite tors.
**Fig. 8.** Images showing a large (12 x 9 m) blocky and thinly-bedded clast of the Caithness Flagstone Group (Devonian), lying at approximately the same topographic level as the stacked Jurassic breccia beds that it is enclosed within. Note that the clast is only just visible on the orthomosaic image (a) but much clearer on the DEM (b). These images were taken just north of the harbour at Helmsdale.

Dems are also able to show the continuity of high and moderate relief beds that are partly underwater. Figure 9 shows a folded part of the succession, with a syncline on the right-hand side of the images (Fig. 9a) and an anticline on the left cut by a boat inlet. The continuity of beds A, B and C in the syncline is obvious (Figs. 9a and 9b). On the ground and in the orthomosaic, their continuation into the anticline and to the north side of the boat inlet also appeared reasonably straightforward with three beds to the south and three beds to the north of the boat inlet (i.e. in Figs. 9b and 9c, southerly bed A = northerly bed B1, southerly bed B = northerly bed B2 and southerly bed C = northerly bed C).

However, because the crest of the anticline is partly eroded and obscured by loose boulders and algae, and much of bed C is permanently in the water the DEM showed that the assumption made in the field and from the orthomosaic was incorrect. Southerly bed A extended under the beach cobbles and was not seen north of the inlet, southerly bed B = northerly bed B1, southerly bed C = northerly bed C, and northerly bed B2 was an additional bed difficult to observe in the field in the south because it is fragmented and is mostly under water (see Fig. 9d).
Fig. 9. Images of the foreshore at Portgower showing how the DEM was used to identify the continuation of folded beds underwater, and across an obscured section and a boat inlet: (a) view of part of the folded beds in the field; (b) orthomosaic image of the beds; (c) DEM of the beds labelled; (d) DEM with the trace of the folds highlighted.
4.5. Earth browser images and 3D textured mesh models

Orthoimages generated as .KML or .KMZ (Keyhole Markup Language and Keyhole Markup Language Zipped) files are useful for virtually revisiting the field location and viewing the terrain of modest variation in topography from different angles and aerial vantage points, and are easy to obtain. These photogrammetry outputs can be viewed in an Earth browser such as Google Earth (the developer of .KMZ files) and show high-quality detail for the imaged section, as well as placing the image within the context of the surrounding landscape captured from the satellite imagery. The files are produced by draping the aerial imagery onto the DEM. In steep terrain this draping produces pixel smear and distortions, but more sophisticated processing can provide full 3D photorealistic models (Pavlis and Mason, 2017).

An example of an orthoimage within the surrounding land- and sea-scape in Google Earth created during this study is shown in Figure 10a. Figure 10b shows a close up, oblique view of some of the beds, looking down dip. The oblique angle here highlights the overlapping depositional geometries of successive beds in the centre of the image better than viewing the orthoimage orthogonally (Fig. 10c).

**Fig. 10.** Examples from Navidale showing how the drone imagery can be inserted into wider landscape views available in Google Earth so that it can be viewed from various directions and angles of elevation. The Jurassic beds in the yellow rectangle in image (a) are shown in close-up in view (b), which is a view seaward from an oblique angle of elevation, and can be contrasted with (c), the orthomosaic image of the same beds viewed from directly above.
A similar output can be made by draping the photographs over the textured mesh. An example of a 3D textured mesh model for each of the areas shown in Figures 8 and 10b can be found as interactive PDFs in the database at DOI: 10.21954/ou.rd.14061734.

4.6. Close up photography

Figure 11 shows the type of detailed images of beds that are inaccessible on foot that can be obtained from the drone camera. The images showed that the upper bed down-cuts into the bed below (Fig. 11a) and allowed analysis of the clast characteristics and distribution (Fig. 11b).

**Fig. 11.** (a) Example of a close-up image of inaccessible beds that can be obtained using the drone from near Navidale (this is one of the most seaward beds in Fig. 10a). (b) an even closer view of the area marked by the yellow rectangle in (a).

5. Discussion

5.1 Advantages of drone images for geological studies

Our drone images of the sedimentary succession near Helmsdale have permitted accurate and precise mapping of the foreshore that had previously proved challenging and resulted in different interpretations (e.g., Fletcher, 1998; Linsley, 1972; MacDonald, 1985). The drone images also revealed large-scale depositional features that had not previously been identified due to partial exposure, size of the features and the limited angle of view. There are virtually no locations along this coast where an elevated view of the foreshore can be obtained. This, together with the difficulty in traversing all the foreshore, meant that it is neither possible to view the beds from far enough away to see large-scale features nor to record all of the small-scale lateral variation across the foreshore. Interpretation of the depositional and post depositional structures was enhanced by being able to view and compare orthomosaic photographs, DEMs, Google Earth .KMZ files and close-up photographs alongside each other and, by having this set of spatial data to check and re-interrogate observations made during ground-based fieldwork. Furthermore, by using this imagery
with ground-based field notes, photographs and GPS locations, it was possible to make measurements in the GIS programme that allowed the construction of generalised graphic logs of short sections that are otherwise inaccessible. This is similar to measurements and graphic logs that have been constructed of inaccessible surfaces or vertical cliff faces from digital models (e.g., Nesbit et al., 2018; Buckley et al., 2019; Priddy et al., 2019; Triantafyllou et al., 2019). Table 2 summarises how each output from our drone survey of the Helmsdale foreshore was used.

Table 2. Uses of various drone image outputs for sedimentological interpretation

<table>
<thead>
<tr>
<th>Use</th>
<th>Orthomosaic photographs</th>
<th>DEM</th>
<th>.kmz files</th>
<th>Close up photographs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral extent of bed</td>
<td>XX</td>
<td>XX</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Related but sedimentologically discontinuous beds</td>
<td>x</td>
<td>XX</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Continuity of beds that are partly eroded or under water</td>
<td>x</td>
<td>XX</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Large-scale post depositional structures</td>
<td>x</td>
<td>XX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-cutting relationships</td>
<td>XX</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Spatial relationship between beds</td>
<td>XX</td>
<td>x</td>
<td>XX</td>
<td></td>
</tr>
<tr>
<td>Facies types</td>
<td>XX</td>
<td></td>
<td></td>
<td>XX</td>
</tr>
<tr>
<td>Bed geometry</td>
<td>XX</td>
<td></td>
<td>x</td>
<td>XX</td>
</tr>
<tr>
<td>Clast size and angularity</td>
<td>XX</td>
<td></td>
<td></td>
<td>XX</td>
</tr>
<tr>
<td>Obscured features</td>
<td>x</td>
<td>XX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurements in GIS</td>
<td>XX</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

XX = very useful – tool of choice
x = useful supplement

In summary, our study and those of others referenced below shows that the overall advantages of using drones are: (i) the ability to obtain higher resolution images than those taken from satellite or manned aircraft (Chandler et al., 2018; Madjid et al., 2018); (ii) the flexibility to take the camera within metres of the object (Madjid et al., 2018), under a variety of light conditions and at different times of day (Dering et al., 2019); (iii) rapid coverage of large (Chesley and Leier, 2018) or difficult to access (Nieminski and Graham, 2017; Triantafyllou et al., 2019) areas; (iv) relatively low costs in terms of the equipment and survey time (Carrivick et al., 2013; Jordan, 2015); (v) safe access to remote or hazardous locations (Salvini et al., 2017; Wakeford et al., 2019); (vi) a continuous dataset obtained by mechanised (therefore uniform / consistent) means (Dering et al., 2019; Nesbit et al., 2018); (vii) new vantage points and angles of view (Cawood et al., 2017; Salvini et al., 2017); (viii) data that can be converted to 3D models and / or image / colour adjustment to highlight features (Bemis et al., 2014); (ix) imagery that allow field exposures to be re-interrogated later (Wilkinson,
(Chandler et al., 2018). In addition, for sedimentary successions, we identified the ability to do the following with drone images as significant advantages: (i) view a sedimentary succession on a range of scales and from different angles; (ii) identify large-scale (tens to hundreds of metres) features such as subtle down-cutting relationships and (iii) make observations on the geometries and large-scale changes in facies and facies associations.

5.2. Digital elevation models

A common challenge in geology is mapping out the original geometry of the beds, especially where the depositional and/or post-depositional structures are complex. In the foreshore this can be hampered by water, modern-day beach deposits and algae but also enhanced by differential erosion where lithological variation commonly gives rise to beds with different elevations above the foreshore. In these cases, to determine the depositional geometry, only the relative elevation is required. The absolute elevation will be affected by factors that are not relevant to the original depositional geometry, including weathering, differential erosion and later structural movements (folding and faulting). In planning for this study we therefore considered the different options for producing a DEM that would provide a relative elevation. These options included using either SfM or LiDAR methods and whether to produce a digital terrain model (DTM) type of DEM which represents the bare rock surface or a digital surface model (DSM) that represents the top of the vegetated (or in this case algae-covered) surface. In particular we sought a method that would work efficiently and effectively in the Helmsdale foreshore where large areas are covered in an unbroken blanket of different algae taxa and smaller areas are buried in sand, cobbles and loose boulders. The algae range from millimetres to a few decimetres thick (most commonly 0.05 – 0.2 m) but is generally thin by comparison with the topography of the breccia beds.

Whilst a DTM might have provided some further information in this setting, the DSM which is created simply, consistently and cheaply from the SfM photogrammetry, served the focus of extracting information on the geometry of the beds in the foreshore well. This was because:

1) To create a DTM from either SfM or LiDAR an algorithm is needed to identify and remove non ground points from the point cloud (e.g. Anders et al., 2019; Chen et al., 2017; Cunningham, 2006) and this is inherently difficult in complex landscapes where there is dense, varied and low ground cover, or sharp changes in ground topography, especially where dense vegetation covers an edge. This difficulty is well acknowledged by those
working on the advancement of both LiDAR DTMs (e.g., Chen et al., 2017; Klápště et al., 2020) and SfM DTMs (e.g., Anders et al., 2019; Klápště et al., 2020). In this study setting the ground surface is complex because there are frequent, abrupt changes of elevation due to the relief of the breccia and some sandstone beds. Furthermore the extensive and particularly dense ground cover means that neither LiDAR nor photographic images would record sufficient true ground points to create an accurate DTM.

2) For LiDAR in particular, wet surfaces and rock pools on the foreshore, together with water covering the beds in the shoreface, would partially absorb the red (near-infrared) laser pulse in a topographic (terrestrial) survey (as opposed to a bathymetric survey which uses blue-green light to infiltrate a water body), leaving gaps in the data. Topo-bathymetric LiDAR using dual red and green lasers, or green only (which will also reflect from land and vegetation) would be required (Mandlburger et al., 2015) but this fast-moving technology is still developing and drone-based topo-bathymetric sensors have only recently become available (Mandlburger et al., 2020).

Despite the high cost of LiDAR surveys, we investigated them in our planning-stage so as to be aware of the optimum possibilities for imaging the area. At the time of our survey, we concluded that neither LiDAR- nor SfM-derived DTMs would have been particularly successful in this setting, without extensive manual adjustments, because of the many and varied complications of the land-sea environment, which make analysis of the foreshore a challenge for any remote data-capture technique.

Had the Helmsdale foreshore been a bare rock surface (where a DSM would be equivalent to a DTM) and cost no object, a LiDAR survey that recorded the reflectance intensity of the returned light pulse, in addition to the return time (i.e. distance travelled) that provides the topographic detail, would have potentially distinguished between the low-relief mudstones and sandstones, based on hard, bright materials having a high reflectance intensity, whilst soft, dull materials have low reflectance intensity (Wilkinson, 2014, 2017). However, in such conditions, the orthomosaic images from a photogrammetric survey would have shown this too because of the colour variation with lithology. LiDAR may however have captured finer topographic detail through direct measurements than SfM photogrammetry, enabling very subtle changes in lithology or elevation to be detected (Wilkinson, 2017).
Both drone-based LiDAR and SfM photogrammetry are fast-moving fields with new, or refinement of, techniques and tools becoming available all the time (Polidori and El Hage, 2020), but as yet, for complex foreshores such as the example used here, the benefit vs. cost ratio of SfM far exceeds that of LiDAR. Furthermore, there were no clear geological observational benefits, in terms of determining the depositional geometry, of the extra processing required to produce a DTM rather than a DSM in this irregular and algal covered foreshore setting.

5.3. Challenges and trade-offs

In a review of the potential of micro drones for geological fieldwork, Jordan (2015) outlined three categories of challenges in their use: natural (wind, rain and the visibility of small drones at a distance), technological (battery size, type of camera lens and scale of view) and legal (regulatory, safety and privacy requirements). For the foreshore environment, in terms of natural challenges, we note that if flights are partly over water it is unlikely that a drone could be recovered if it ditched, unless designed for water landing; sea fog can quickly develop, requiring the termination of flights; and birds present an additional hazard. In addition, temperature is a major concern for battery and motor performance in both hot and cold ambient temperatures. For the Mavic Pro drone used in our study, the manufacturer’s guidelines state a 5–40°C operating temperature range (https://store.dji.com/product/mavic-intelligent-flight-battery). These batteries measure their internal temperature and the flight control system will warn against flight if the batteries are below 12°C. In such conditions a thermally insulated container can be used to maintain this temperature, and once in flight the battery generates enough internal heat to sustain their operational performance, though testing and caution is advised, depending on the local conditions and operator experience. All of these difficulties and those outlined below, were anticipated in the foreshore setting in NE Scotland during the planning stage and where possible, measures were put in place to overcome them prior to fieldwork. The foreshore setting presents unique natural challenges, which require four trade-offs to obtain optimum quality imagery of the maximum extent of exposed foreshore rock possible in the time available. These are:

1. **Time of year to balance the algal cover versus bad weather**: the calm, dry weather needed to operate a drone is most likely in spring or summer, but algae tends to be at its lowest abundance on the foreshore at the end of the winter and develops through the spring and summer. In NE Scotland, we opted for early May, although several successive years with few winter storms meant that the algae had not been removed during the winter. Summer months
also give the longest and brightest hours of daylight, making it more likely that a low tide will be in good daylight.

2. **Tidal range versus algal cover:** the tidal range and extent of the algal cover need to be balanced. For the Helmsdale area, a week in May with spring tides during daylight hours was chosen to maximise the foreshore exposure that is visible. Although the level of low spring tide decreased further towards the autumn equinox, the summer period coincides with an increase in algae. The lowest tides in winter months all occurred during darkness.

3. **Evening light versus morning light and shadows versus glare:** the variation in the natural lighting during the day needs to be carefully considered to maximise illumination of the areas of interest. Low tides on our chosen week were early morning and early evening, with the lower of the two tides being in the morning. At both times, shadows are cast behind the elevated breccia beds. However, a midday sun would have produced glare on the water. With low-angled sunlight, the drone cameras were better able to image submerged rocks, even without a polarising filter on the camera. The low-angled light also enhanced definition of features. Although evening light illuminated the more informative scarp face of the breccia beds, we opted to work early morning as the sun quickly dipped behind hills in the evening, cutting short our low-tide window.

4. **Flight elevation and hence resolution versus time available at low tide:** the resolution of the photogrammetric outputs (dense point cloud, textured mesh, DEM and orthomosaic) is dependent on the flight altitude, camera quality and number of aligned points in the sparse cloud that the computer processor can handle. The flight altitude also dictates the time taken to survey a set area. In Helmsdale, the rocks were exposed for about three hours around low tide; lowest tides lasted for 3–4 days and were at an acceptable level for a week, allowing contingency time. By flying the drone at 50 m elevation, we covered five c. 1 km x 200 m sections of foreshore (c. 1 km²) in five hours of flying time over three days, equating to c. 100,000 m² in 30 minutes. This gave a resolution of 1.6 cm per pixel in the orthomosaic images allowing us to easily identify objects of at least 0.10 m. The SfM photogrammetry DEMs constructed here have a resolution of 3.5 cm / pixel. By comparison, in a high-resolution survey, Vollgger & Cruden (2016) carried out a 25 minute flight over a wave cut platform at low tide at an average elevation of 38 m (8 flight lines and one at 53 m) to cover a 13,000 m² area and obtained a ‘sub-cm resolution’.
Positional accuracy errors from our approach were estimated by Agisoft PhotoScan to be on the order of 0.76 m. These are large relative to professional survey grade approaches, but were perfectly adequate for the purposes of our survey and indeed for many geological purposes. In cases where a higher accuracy survey is required, the use of RTK drone equipment could be considered as this is now becoming more affordable and could preclude the need for ground control points positioned using RTK GPS/GNSS equipment. However, Riley and Wilkinson (2018) note the possibility of errors of up to 2 m because of drone movement and positioning of equipment.

Our suggested step-by-step method is summarised in Fig. 4 and our best practice points for gathering drone images of any foreshore setting are:

- Research the survey location well in advance of the drone field campaign to identify local airspace and regulations, meteorology, landownership and access, human activity, infrastructure, terrain, wildlife and access/escape points.
- Obtain tide timetables well in advance; select the month / week for the campaign to coincide with optimal tides for exposure and lighting conditions.
- Make timing trade-off decisions relating to the timing of the work to balance algal cover, bad weather, lowest spring tides, and angle of light to reduce shadows and glare.
- Establish the field team required. Have a big enough team to cover essential tasks – pilot, camera operator (if two operators are required), setting up ground control points, spotters, runners and base contact. Ensure the pilots are experienced with the drones before the field campaign in order to enhance the probability of obtaining satisfactory data and minimising risk as most field locations present a number of natural and logistical challenges.
- Make technical trade-off decisions relating to image quality, data storage and handling capabilities and the time available.
- Carry out detailed advance planning of the flights, defining the objectives and dividing the work into prioritised daily segments. Plan redundant time to allow flexibility if weather conditions do not permit flying.
- Ensure landowner permissions, Risk Assessment and Method Statement, insurance, communication with air traffic control authorities and other required documentation for the location are in place to ensure compliance with current aviation, privacy, and health and safety regulations and best practice.
• Follow the pre-flight checklist (Fig. 4) before each flight and undertake a debrief at the end of each flight, updating the RAMS where required.

• Use high-quality, easily transportable equipment, ensuring the drones selected are suited to your field location, purposes and the pilot’s training and experience.

• Allow contingency for equipment (extra batteries, more than one drone, backup communications options) and people in addition to time for bad weather.

• Have sufficient data storage and computing power in the field (for large quantities of high-resolution images) and later when processing and using the data, as the associated file sizes and types can be computationally intensive.

The technical capabilities of recreational drones are increasing and may, in the near future, prove reliable enough to produce good data during the rigours of geological fieldwork. A current consideration is that recreational drones are not integrated with software to plan and control the flight paths and are not able to carry payloads. Nevertheless, there is no doubt that the new vantage point and the scalable data provided by drones offers significant advantages to geological studies even before more sophisticated remote sensing instruments or complex processing is considered. Importantly though, the method outlined in this paper, including adhering to all of the regulations for the flying of professional drones such as seeking permission from landowners, safety and airspace regulations, still apply to recreational drones. We strongly advise following good responsible practice and up-to-date, locally-relevant legislation when collecting geological data using drones.

6. Conclusions

High-resolution geo-referenced imagery of sedimentary features from drones considerably aids sedimentological studies in poorly accessible and variably exposed locations. The use of drones greatly increases the amount of data that can be gathered in the often-limited time available for fieldwork. Unlike photographs, drone-SfM images provide full spatial coverage at a range of scales and the ability to view dipping rocks in horizontal and subhorizontal exposures from different angles and vantage points. The foreshore is a unique setting with unavoidable time constraints caused by the tidal cycle, and the weather and daylight hours associated with the latitude of the field location. This leads to the need for compromise decisions to be made if the maximum rock exposure and best possible image resolution is to be captured in the time available. Our study has
illustrated a best-practice, budget-limited approach for the gathering of drone data for geological studies of the foreshore.

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