Generating photogrammetric DEMs in the field from remotely piloted aircraft systems

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Abstract

Remotely piloted aircraft systems (RPAS) can be used in the field to acquire air photos which can subsequently be used to produce digital elevation models (DEM) and orthomosaics. In this study, we examined if field-generated photogrammetric DEMs in a remote, sparsely vegetated mountainous region of north-central British Columbia are of adequate resolution to guide surficial geology mapping. Using a quadcopter RPAS with real-time kinematic (RTK) positioning, we conducted 16 flights (more than 150 line-km), taking photographs with a visible-light RGB digital camera equipped with a 1-inch CMOS sensor and mechanical shutter. Once programmed using flight-planning software, the aircraft flew itself although, as required by federal regulations, we maintained continuous visual line-of-sight. The aircraft flew at a speed of 4 m/s, at heights of less than 120 m above ground, and with a line spacing that gave 70% horizontal overlap (side lap) and 80% vertical overlap (end lap). We processed the air photos in the field using structure from motion (SfM) photogrammetry to create topographic DEMs. With resolutions of <10 cm/pixel, these DEMs rival those produced using lidar in unvegetated areas. Easy to acquire, affordable, and immediately accessible, the DEMs provided details in near real-time about surficial deposits that field crews would not otherwise have gained. Not only did the DEMs help us better define deposit types, they enabled us to gather data on movement of glaciers during the Late Wisconsinan by highlighting landform-scale streamlined features that could not be identified on air photos nor measured on the ground.

Keywords: Remotely Piloted Aircraft System (RPAS), Unmanned Aerial Vehicle (UAV), drone, photogrammetry, Digital Elevation Model (DEM), Agisoft Metashape Professional, DJI Phantom 4 Pro, Real-time Kinematic, surficial geology

1. Introduction

Remotely piloted aircrafts (RPAs) are defined as any navigable aircraft where a pilot is not onboard (Transport Canada, 1996). More commonly, RPAs are referred to as drones, unmanned aerial vehicles (UAV), or unmanned aircraft systems (UAS; Carrivick et al., 2013; Niedzielski, 2018). In the last five years, remotely piloted aircraft system (RPAS) technology has progressed to a level where publication-quality data can be captured by small, commercially available systems (Chabot, 2018). The use of RPASs in the field has become more common as user-friendly, commercially available aircraft systems and high-performance portable computers have become available. RPAS and photogrammetric technology can now be used as a complete, self-supported package, deployable using small, one- or two-person crews. Current photogrammetry software does not require the use of internet or office resources, a prerequisite to any technology that is to be used in the field. High processing speeds allow dense photogrammetry datasets to be obtained and processed in near-real time. By incorporating RPAS technology in a field program, scientists can access more information in remote locations.

In this study, we test if field-generated photogrammetric DEMs in a remote, sparsely vegetated mountainous region are of adequate resolution to guide geologic mapping. To support ongoing surficial and bedrock (Ootes et al., 2019, 2020) mapping projects, in the Hogem batholith area of north-central British Columbia (Fig. 1), we flew 16 RPAS surveys, testing if the constructed DEMs provided significant insights that otherwise might have been missed. Herein we report on two of these surveys focussed on surficial deposits. Not only, in both cases, did the DEMs help us better define deposit types, in one case they enabled us to gather data on movement of the Late Wisconsinan Cordilleran Ice Sheet by highlighting streamlined features that could not be identified on air photos nor measured on the ground.

2. Background

2.1. Remotely Piloted Aircraft Systems (RPAS)

Rapid advancement in RPAS and payload technology is contributing to dramatic changes in field-based remote sensing. Satellites and piloted aerial surveys have been major contributors to imagery for geological mapping since the late 1950s (Hansman and Ring, 2019). Although these methods produce high-quality imagery, they are time consuming or expensive (Hansman and Ring, 2019). Miniaturization of aircraft and sensors has led to small, affordable, and commercially available RPASs becoming more common as tools in scientific research and industry activity (Chabot, 2018). Early versions of RPA have wing spans of several metres and require a highly trained pilot to fly. Today, RPA pilots can fit

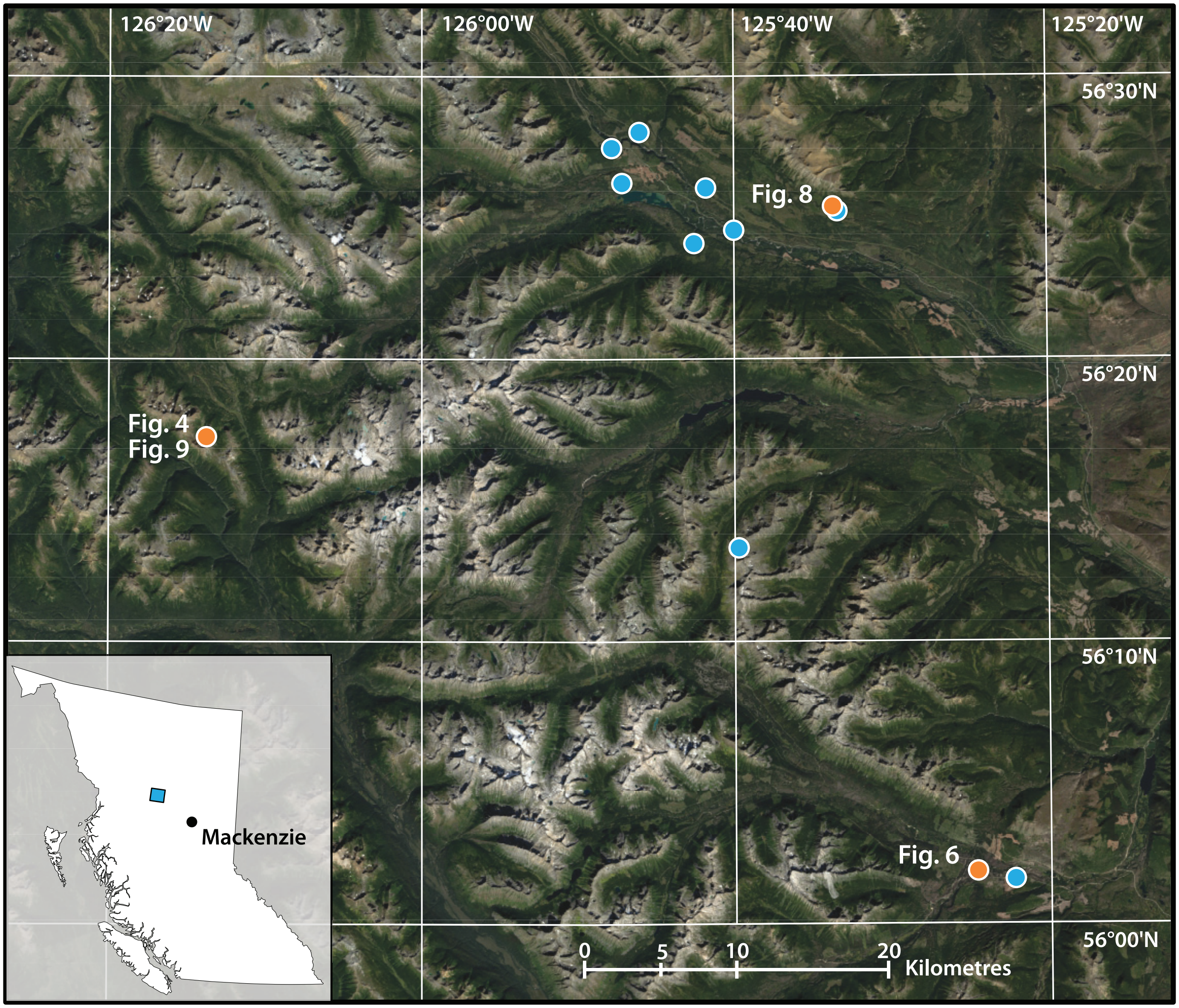

Fig. 1. Remotely piloted aircraft system flights conducted in the Hogem batholith region. Location of RPAS air photo flights are shown with blue points. Locations of case study flights are shown with orange points. Multiple flights conducted from the same take off location are represented by a single point.

an aircraft into their backpack and fly the machine with little training. Images acquired by an RPA are more affordable then most aerial imaging techniques and the time required for planning, capturing, and processing is faster than most traditional methods (Carrivick et al., 2013). An inexpensive RPA equipped with an RGB camera can be used to provide a new aerial perspective to geologists and access places that are impossible or unsafe to reach by foot. Areas like cliff faces and steep ridges can be safely and easily accessed, acquiring images within metres of the ground without the interference caused by downwash of conventional helicopter rotors. Images captured by an RPAS can be used as stand-alone products, viewed in stereo, or can be manipulated using photogrammetry software.

Multiple rotor RPASs constitute the latest advances in remotely piloted aircraft. With four rotors providing effective lift and maneuverability, quadcopters have many advantages over other RPAs including their ability to carry heavy payloads, hover in position through heavy winds, complete a vertical take off and landing (VTOL), and produce high-quality, precisely located aerial photos (Carrivick et al., 2013). Quadcopter RPAs also contain an onboard computer used for autopilot capabilities, allowing the RPA to take off, fly, and land with little input from the pilot (Carrivick et al., 2013). Onboard flight assistance systems help maintain stable flight and avoid collisions with the ground and other static objects. Using flight-planning software, specific survey grids can be constructed, and an area can be flown on autopilot following a designed flight path. However, quadcopters are not the only RPASs capable of remote sensing and photogrammetry. A range of single propeller, multirotor (e.g., octocopter) and glider RPAs are also available.

All RPASs used for conducting aerial surveys are equipped with GPS receivers that collect spatial information associated for each photograph. Real-time kinematic (RTK) positioning is a method used to enhance the precision of data collected from Global Navigation Satellite System (GNSS), a satellite-based system with global coverage. The USA's GPS GNSS is the most known, but Russia (GLOSNASS), the European Union (Galileo), and other countries have deployed and maintain their own GNSS. The satellites in each of these systems form an Earth-orbit constellation, allowing multiple satellites to be in range of a receiver at all times, thereby increasing accuracy and reliability. An RTK base station receives spatial data from GNSS satellites, calculates positional corrections based on carrier wave phase, and forwards corrections wirelessly to the RPA in real-time. The RPA uses these corrections to improve in-air positioning. Because of this, each RPA photo has a very precise 3-dimensional coordinate associated with it. Another benefit of using RTK technology is that, in specific situations, it eliminates the need for ground control points (GCPs), which are targets placed throughout the survey area to provide accurate positional information. Eliminating GCPs reduces the amount of set-up time for each survey, as well as time required for post-processing.

RPASs can provide high-quality, cost-effective, imagery ideally suited to multitemporal surveys in regions undergoing continuous changes that require monitoring by repeated surveys. For example, the Newfoundland Geological Survey has been using RPASs for several years to assess coastline stability and hazards (Irvine et al., 2018). Other examples include monitoring rock glacier movement (Kaufmann et al., 2018), investigating landslide topography (Niethammer et al., 2010), repeat characterization of landslide-prone areas (Rossi et al., 2018) and soil erosion studies (D'Oleire-Oltmanns et al., 2012). RPAs can also be used to construct digital bedrock outcrop models, extracting structural information, allowing the configuration of dipping rock units to be assessed and measured in the digital environment (Zahm et al., 2016). Some of the challenges around RPAS use in the field include: the limited number of sensors and aircrafts available on the market; country-specific above ground level (AGL) and visual line-of-sight regulations; and field logistics related to recharging multiple, high-capacity batteries.

2.2. Photogrammetric DEMs

Standard photographs acquired by an RPAS can be uploaded onto a high-performance computer to generate a photogrammetric digital elevation model (DEM), which is a representation of a surface created by processing multiple overlapping RGB photographs. Photogrammetry software extracts a large amount of information per image to place and orient topographical data in real space, producing a DEM (Hansman and Ring, 2019). The photogrammetric process begins with the identification of key points in each uploaded photo. These key points can number in the 10,000s per image and are placed in locations that can be recognized in each overlapping photograph (Hansman and Ring, 2019). Modern photogrammetry software calculates key points by a structure from motion (SfM) algorithm. SfM photogrammetry uses images taken at varying distances and angles to construct models, as apposed to a systematic grid required for traditional photogrammetry (Johnson et al., 2014; Hansman and Ring, 2019). Images acquired with RTK positioning provide SfM photogrammetry software accurate photograph locations, allowing models to be produced faster and more accurately. The position of overlapping key points is triangulated in multiple photographs to create a single tie point, stitching the photographs together. The photogrammetry software identifies an x-y-z coordinate for each tie point and places it into real space. Once a large number of tie points are positioned, a manipulatable point cloud model representing the geometry of the captured scene is created (Hansman and Ring, 2019). Spaces between tie points can be interpolated, leading to the generation of a DEM. The resultant DEM can be manipulated in a geographic information system (GIS) to produce hill-shaded models and a range of other products.

Digital elevation models can be produced using other methods and sensors including light detection and ranging (lidar). Lidar is an active, aircraft mounted sensor that emits a laser pulse (upwards of 50,000 Hz) and records the laser's reflected travel times. Last returns in a lidar point cloud can represent laser light reflected off the Earth's surface, beneath vegetation or tree canopies. These last returns are used to produce a bare-Earth DEM, or a model of the Earth's surface without vegetation. In contrast, photogrammetric DEMs are produced using reflected, visible light photography and cannot produce a bare-Earth model in fully treed areas. However, in areas of sparse ground cover, photogrammetric DEMs can rival lidar-generated DEMs (Johnson et al., 2014). Some SfM photogrammetry software can recognize trees and eliminate them from the final DEM. This is useful for regions with sparse tree cover. When producing models of heavily forested regions, so little of the ground is imaged that large holes exist in the DEM where the forest canopy once was. For this reason, bare-Earth photogrammetric DEMs can only be produced in regions with low levels of vegetation.

3. Geologic setting

In the Hogem ranges of north-central British Columbia, about 200 km northwest of Mackenzie (Fig. 1), our study area is a steep mountainous terrain with northward facing cirques and deep U-shaped valleys (Holland, 1976). The area is remote and road access is limited to larger valleys with a history of logging activity. Valley bottoms commonly contain thick and laterally extensive glaciofluvial deposits, and hummocky deposits that range in height from 1-10 m and extend for 100s of metres. Undulating and streamlined till, and colluvial aprons and fans, with sparse bedrock outcrop, are common on valley sides adjacent to glaciofluvial deposits. Cirques and arêtes are predominant in alpine regions, locally containing remnant ice, with intervening low-gradient slopes or plateaus consisting of felsenmeer. Although bedrock outcrop is exposed continuously in these high elevation settings, it is difficult to find glacially polished or striated outcrop used to reconstruct ice flow history.

The Hogem batholith is a composite intrusive body consisting mainly of felsic to mafic plutonic rocks that show significant local variation (for details see Ootes et al., 2019; Ootes et al., 2020). The batholith has high potential to host syngenetic porphyry-style Cu (±Au, Ag, Mo) mineralization and quartz vein-hosted concentrations of precious and base-metals. Northwest of the study area (70 km) is the past producing Kemess mine (calc-alkaline porphyry Cu-Mo-Au) and to the south (10 km) the Lorraine developed prospect (porphyry alkalic Cu-Au).

Air photo surveys were flown in areas of sparse to no vegetation such as cut blocks, cirques, mountain tops, and areas with burned or disease-infected trees. Recent, unplanted, cut blocks are ideal to conduct an RPAS survey due to their lack of vegetation, allowing clearer photos to be taken of the ground surface, but also because they allow a large area to be covered while maintaining visual line-of-sight (VLOS) with the aircraft.

4. Methods

4.1. Air photo acquisition

A DJI Phantom 4 Pro RTK RPAS was used to conduct each survey (Fig. 2). This RPAS is equipped with a fixed payload RGB camera that has a 20 mega-pixel, 1-inch CMOS sensor, and a mechanical shutter. A mechanical shutter does not produce wobble associated with a rolling shutter, commonly known in photogrammetry as the 'jello effect'. The camera is attached to the airframe by a three-axis gimbal, which provides image stability and allows for in-flight adjustment of camera angle. Practical flight time for the Phantom 4 Pro RTK is approximately 25 minutes per battery. Ground control points were not used during our surveys. The positional accuracy of the Phantom 4 Pro RTK, as stated by the manufacturer, is approximately 2.00 cm vertically and 1.20 cm horizontally, when flying at 33 m above ground level.

All survey areas were accessed by truck or helicopter. We selected sites that had a surficial or bedrock geology unit of interest, lacked trees, and permitted us to maintain VLOS while flying within 120 m above ground level. The outer bounds of the survey area were first flown without using autopilot. The track recorded in DJI GS RTK flight-planning software was then used to design the survey, which was flown using the autopilot function (Fig. 3). Missions were flown between 50 m and 100 m AGL, with 70% horizontal overlap (side lap) and 80% vertical overlap (end lap). Aircraft speed was maintained at 4.0 m/s to minimize distortion caused by a moving camera. Survey flight times ranged from 20 to 60 minutes, including initial set up, mission design, and completion. Surveyed areas ranged from 15,810 to 424,251 m^2. Precautions were not taken for light conditions or sun altitude.

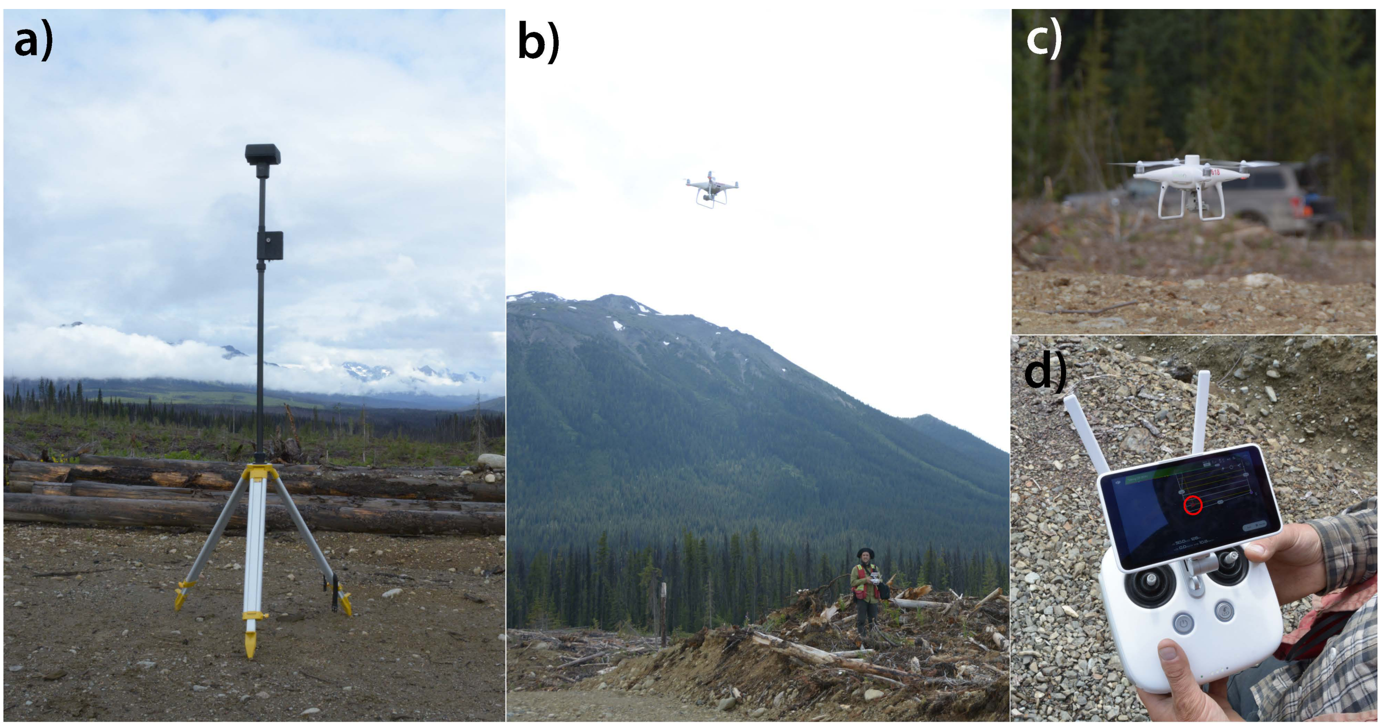

Fig. 2. Equipment used in the field that makes up the RPAS. **a)** RTK mobile base station. **b)** DJI Phantom 4 Pro RTK being operated remotely by pilot on-ground. **c)** DJI Phantom 4 Pro RTK in flight with the camera facing away from the viewer. **d)** DJI Remote control, with DJI flight-planning software DJI GS RTK on screen, showing location of RPAS (red circle) while conducting an air photo mission autonomously in auto pilot mode following pre-planned flight lines.

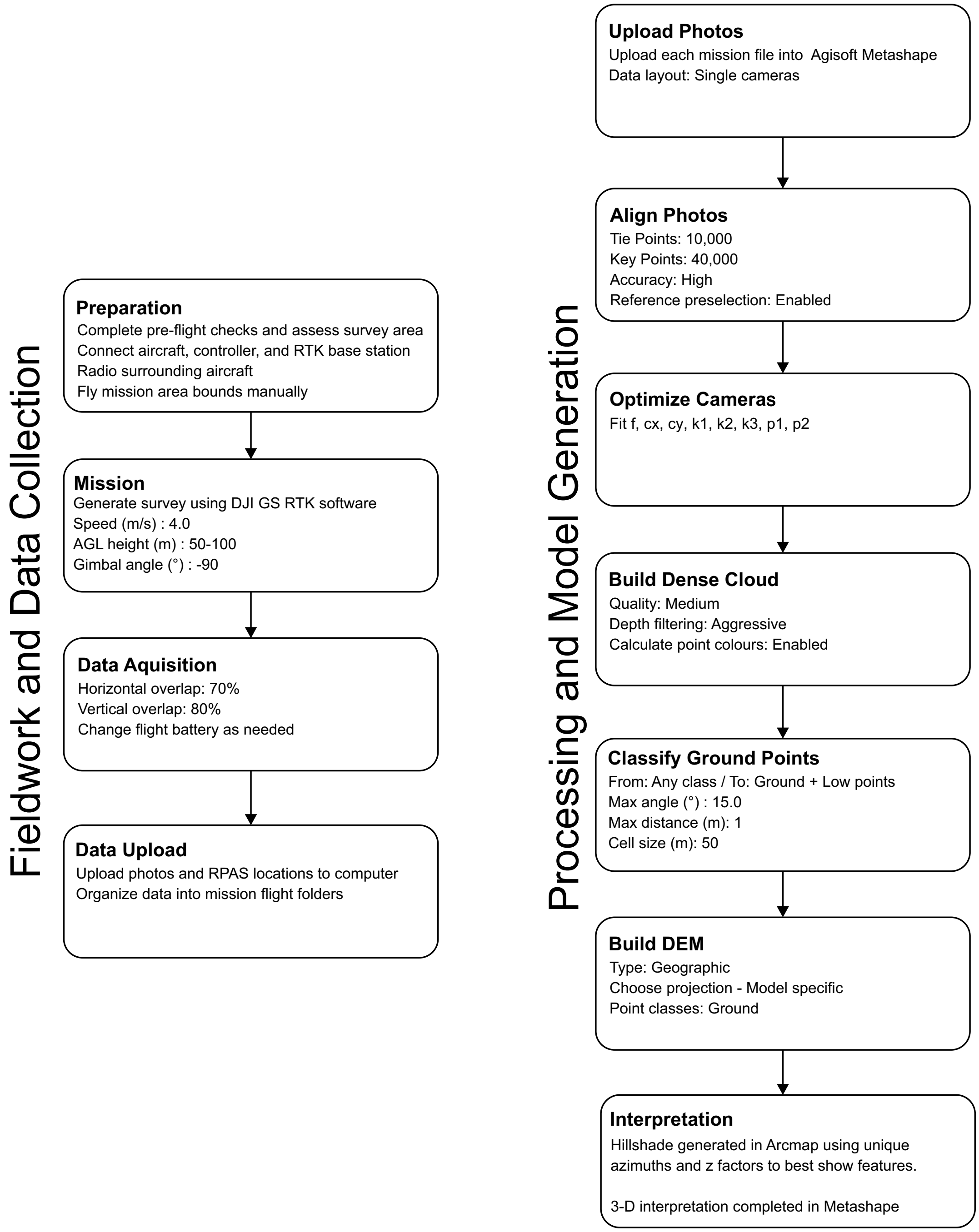

Fig. 3. Flight and data workflow for typical generation of photogrammetric DEMs.

4.2. Data processing

Agisoft Metashape Professional was used in the field to produce photogrammetric DEMs from air photos acquired by the RPAS. Metashape is a simple, yet powerful, application intended for a variety of 3D modelling purposes and is not limited to constructing DEMs. One advantage of Metashape for remote field work, is that it is not built on cloud processing; all processing is done locally on a personal computer running the software. Metashape is also considered a complete package, allowing a DEM to be generated solely using a single application. Other DEM production software requires switching between multiple programs for each step in the generation process (Johnson et al., 2014). Metashape's batch processing feature allows parameters for each step to be specified beforehand. Using this feature, a product is generated from start to finish without requiring the user to watch over the process.

Metashape works efficiently with RTK data, importing all metadata associated with RPA position, pitch, roll, and yaw for each captured photograph. Processing was completed on a laptop running a 2.2 GHz Intel Core i7 CPU, 32 GB RAM, and an NVIDIA Quadro P3200 graphics card. Processing a survey with 300 individual photographs, 4.5 x 10^5 sparse points, and 4.0 x 10^7 dense points at a high-resolution takes approximately 3 hours. Eight years ago, a survey with a similar number of dense points would take 7 to 56 hours on a high-end desktop computer using similar SfM processing techniques (Westoby et al., 2012).

When working to generate a photogrammetric DEM, three other products are produced: a dense point cloud, textured mesh, and orthomosaic. A dense point cloud is created from further interpolation of each photo, adding more calculated points to the sparse point cloud model. This produces a dynamic, three-dimensional model constructed from millions of individual points, each with an assigned RGB colour. A dense point cloud can be manipulated in 3D space and viewed from any perspective (Fig. 4). Although a dense point cloud does not replace a true 3-dimensional model, it can be generated very quickly to gain a rudimentary understanding of topography. An orthomosaic is a geometrically rectified compilation of aerial images that allows measurements to be taken directly from the image in real-world units. High-resolution orthomosaics are an ideal base layer for mapping large-scale geologic features. A textured mesh is a true 3-dimensional model, with a triangulated network of points and a solid coloured surface. The solid surface fills the holes produced in point cloud models.

5. Results

We conducted 16 individual surveys using the Phantom 4 Pro RTK RPAS to capture high-resolution, nadir imagery. The resultant images were processed in the field, producing photogrammetric DEMs and point cloud models for each mission. Below we present the results from two of these missions. One was flown over hummocky terrain, the other over glacially streamlined terrain (Table 1).

Table 1. Summary of RPAS air photo survey parameters.

	Hummocky terrain	Glacially streamlined terrain
Flight time	50 min	30 min
Processing time	4 hr	2 hr
Area	386,100 m^2	11,500 m^2
Photos	676	277
DEM resolution	9.66 cm/pixel	9.09 cm/pixel

5.1. Hummocky terrain

In this terrain, hummocks that are 1-10 m high extend for 100s of metres and are mantled by large (up to 1 m) boulders (Fig. 5). On the basis of roadside exposure, we originally considered that these are stagnant ice glaciofluvial sand and gravel deposits. Most of the standing trees in the area were recently burned and lack foliage.

We created a photo density map (Fig. 6a) showing the RPA path (northeast-southwest) and the degree of redundancy in image collection. Each black point represents the location of an image and the colour ramp shows the number of adjacent overlapping photos. The density of photos corresponds to point density in cloud models (Johnson et al., 2014). A greater point density results in higher resolution models, and more redundancy in the data allows positions to be more accurately represented. For nearly the entire extent of the surveyed area, >9 overlapping photos were used to create the dense point cloud.

Metashape's 'classify points' function was applied to the dense point cloud to identify low-lying points and ground points, based on maximum slope of changing terrain, distance between points, and cell size of classified features. Unclassified and low-lying point classes were subtracted from the dense point cloud and the resultant photogrammetric DEM represents a pseudo bare-earth model, consisting of solely ground points (Figs. 6b, c). The central portion of the DEM, shown in detail in Figure 6b, is clean where vegetation consists of standing dead and fallen trees. The regional DEM has a rougher texture where low-lying vegetation or trees could not be completely removed from the dense point cloud (e.g., northeast and southeast corners) and is overly smoothed where bare earth could not be imaged over entire regions of dense forest (e.g., east margin). This is due to the software building a DEM with very few remaining points. Without many points to reference, the software produces a low-resolution, smoothed model.

The photogrammetric DEM extended ground observations to a much larger area and it also allowed us to recognize a second deposit type. Using the DEM, we found that the hummocky glaciofluvial sands and gravels we considered stagnant ice deposits at road exposures extend northeast for >500 m and southwest for >200 m. In addition however, in the western part of the photogrammetric DEM are features with a channel-like geometry that were not observed from the road. These are likely glaciofluvial sediments that were deposited by meltwater systems. Thus, based on the DEM, we now recognize that the survey area includes two genetically distinct deposits, stagnant ice hummocky drift and a glaciofluvial blanket.

5.2. Glacially streamlined terrain

This survey was conducted in a recent forestry cut block underlain by till that we originally considered a veneer or blanket deposit, and local bedrock outcrop. Most of the timber left from logging is stacked in slash piles along the cut-block periphery. Nonetheless, the cut-block floor is still obscured by stumps, leftover woody debris, and saplings (Fig. 7a). Although topographic relief is subtle (<1 m), discontinuous positive linear features extend through the cut block. Because of scale and tree cover, these features cannot be recognized in 1:40,000-scale black and white air photographs (Fig. 7b). Furthermore, because of their low relief, the geometry and orientation of the features are difficult to establish on the ground. We flew the survey to investigate these features and combined the survey with ground observations, particularly near small (~2 m^2) bedrock outcrops.

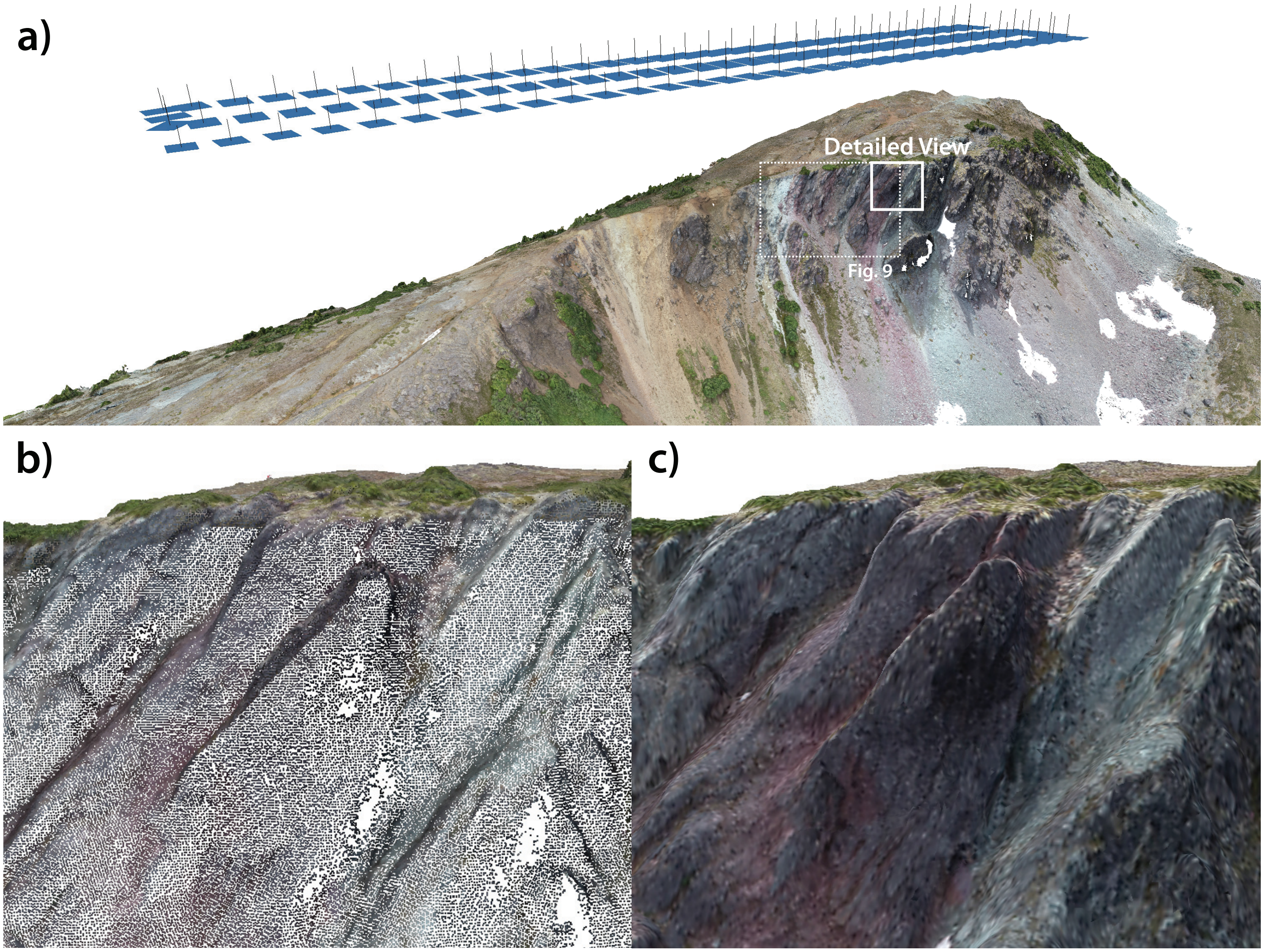

Fig. 4. Point cloud and textured model of a bedrock ridge. **a)** Dense point cloud model. Blue rectangles over ridge represent air photo locations, with black vertical lines oriented normal to the image plane. **b)** Detailed view of dense point cloud model. Each point has an x,y, and z coordinate and is coloured based on RPAS air photos. **c)** Detailed view of textured mesh model. This image covers the same area represented in b), but here the dense point cloud model is draped with a raster image, thereby removing empty spaces between points. See Figure 1 for location.

Fig. 5. Oblique photograph of hummocky terrain in RPAS survey area. Photo taken from RPA.

The dense point cloud was classified into ground points, low points, and unclassified points using Metashape. The unclassified points and low points were not used to produce the final DEM surface (Fig. 8). The area to the north and south of the DEM was cropped due to being heavily forested and at a poor resolution. The DEM was then imported into ArcMap, where a hillshade model was created using a unique azimuth and altitude to best display the streamlined terrain.

The photogrammetric DEM produced for this region shows that the discontinuous positive linear features identified on the ground, are fully continuous for up to 75 m, approximately 10 m wide and 1 m high (Fig. 8). Highlighted in the central part of the DEM (Fig. 8), parallel ridges are organized en echelon, oriented east-southeast, and can have bedrock outcropping on their western ends. In plan view, these features have longitudinal asymmetry, tapering from outcropping bedrock on their stoss

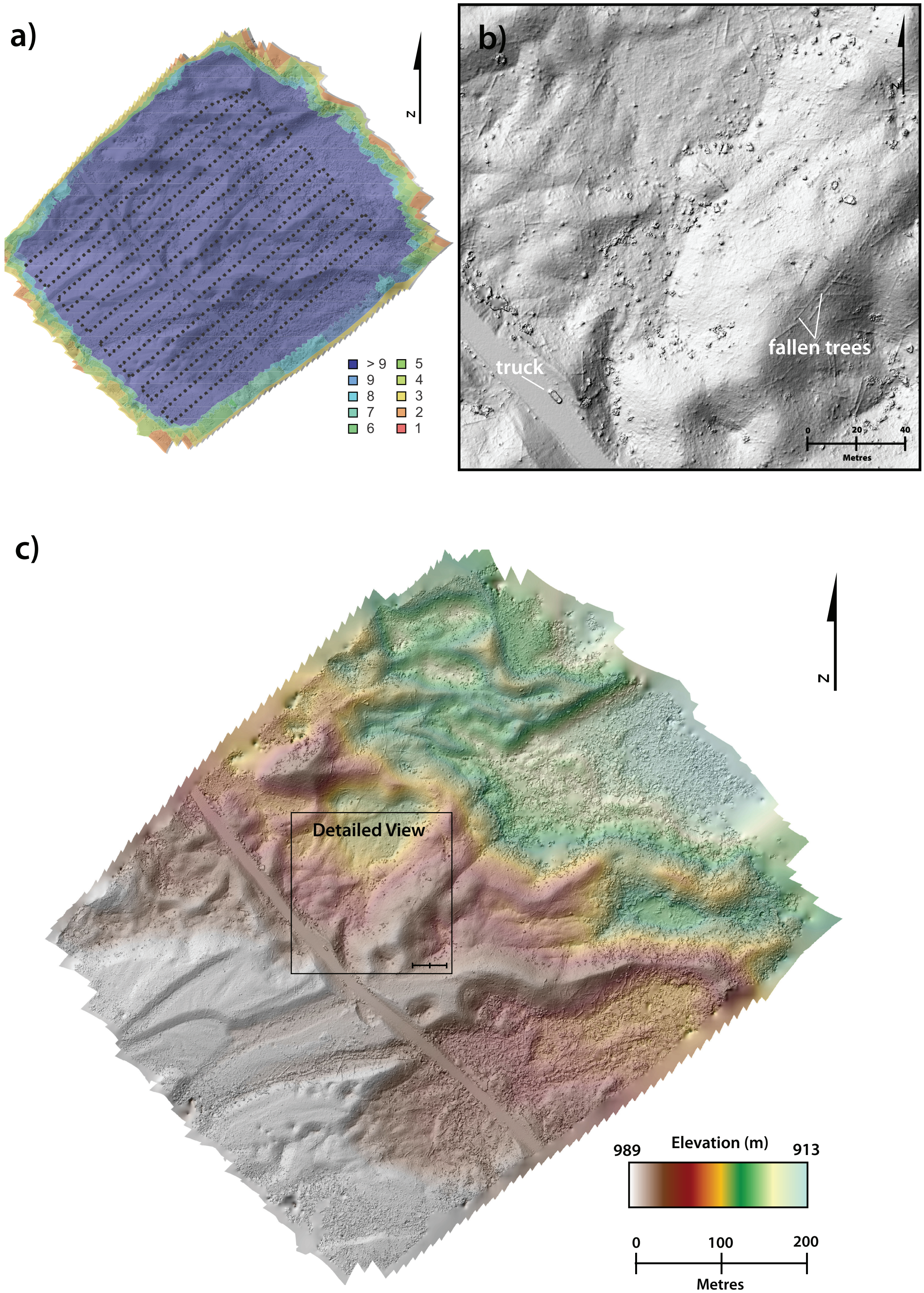

Fig. 6. Hummocky terrain survey area. **a)** Photo density model. Each point represents a RPAS air photo location, with each colour representing the number of overlapping photos used to create the photogrammetric DEM. See Figure 1 for location. **b)** Detailed view of survey area. Fallen trees are represented by linear, criss-crossing objects. **c)** Photogrammetric DEM of ice contact and channelized glaciofluvial sediments.

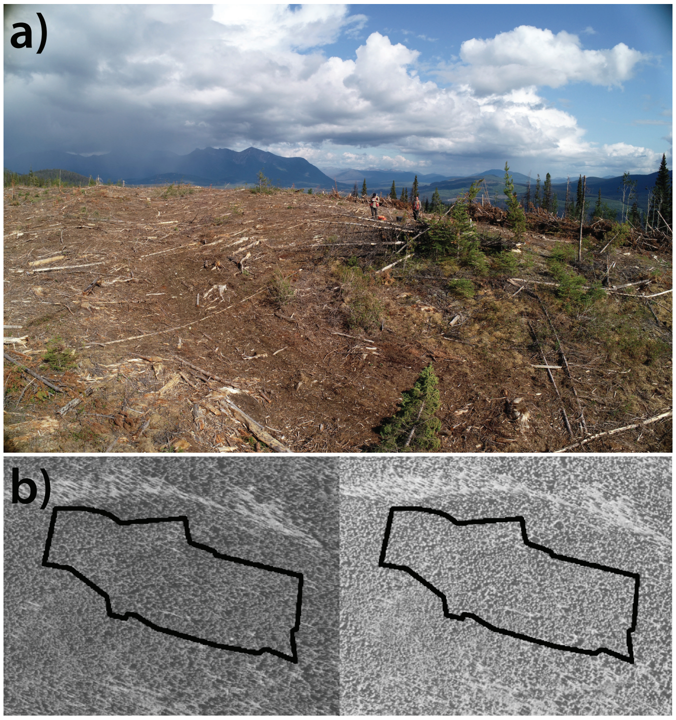

Fig. 7. a) Oblique photograph of glacially streamlined terrain. Photograph taken from RPA. **b)** Black and white, 1:40,000-scale air photo stereopair of same area. Tree canopy masks subtle streamlined features observable in photogrammetric DEM.

end to their leeward side composed of a diamicton. Crag and tail ridges are unidirectional, glacially streamlined landforms created by the deposition of sediments on the lee side of an eroded bedrock obstacle. Although the features seen in the DEM are low relief, they are interpreted as small crag and tail ridges and their orientations indicate east-southeast movement of glaciers through the region during the Late Wisconsinan. These small crag and tail features sit on a larger bedrock high that itself is streamlined in the same direction (see red to white elevations, Fig. 8). A smaller streamlined ridge, just north of this larger feature, indicates more easterly flow. This could be a product of ice deflecting around the larger topographic high.

The photogrammetric DEM showed us that deposits in the clear cut are not part of a till blanket or veneer as we previously thought, but rather part of a glacially streamlined terrain with ice-flow direction significance. This conclusion prompted us to fly another RPAS survey in similar terrain that also resulted in a change in deposit type designation from till blanket to streamlined till. Although the crag-and-tail streamlined features are rare in the Hogem batholith area, they can guide bedrock mappers to isolated exposures in largely drift-covered areas because outcrops are likely at or close to surface at their stoss ends.

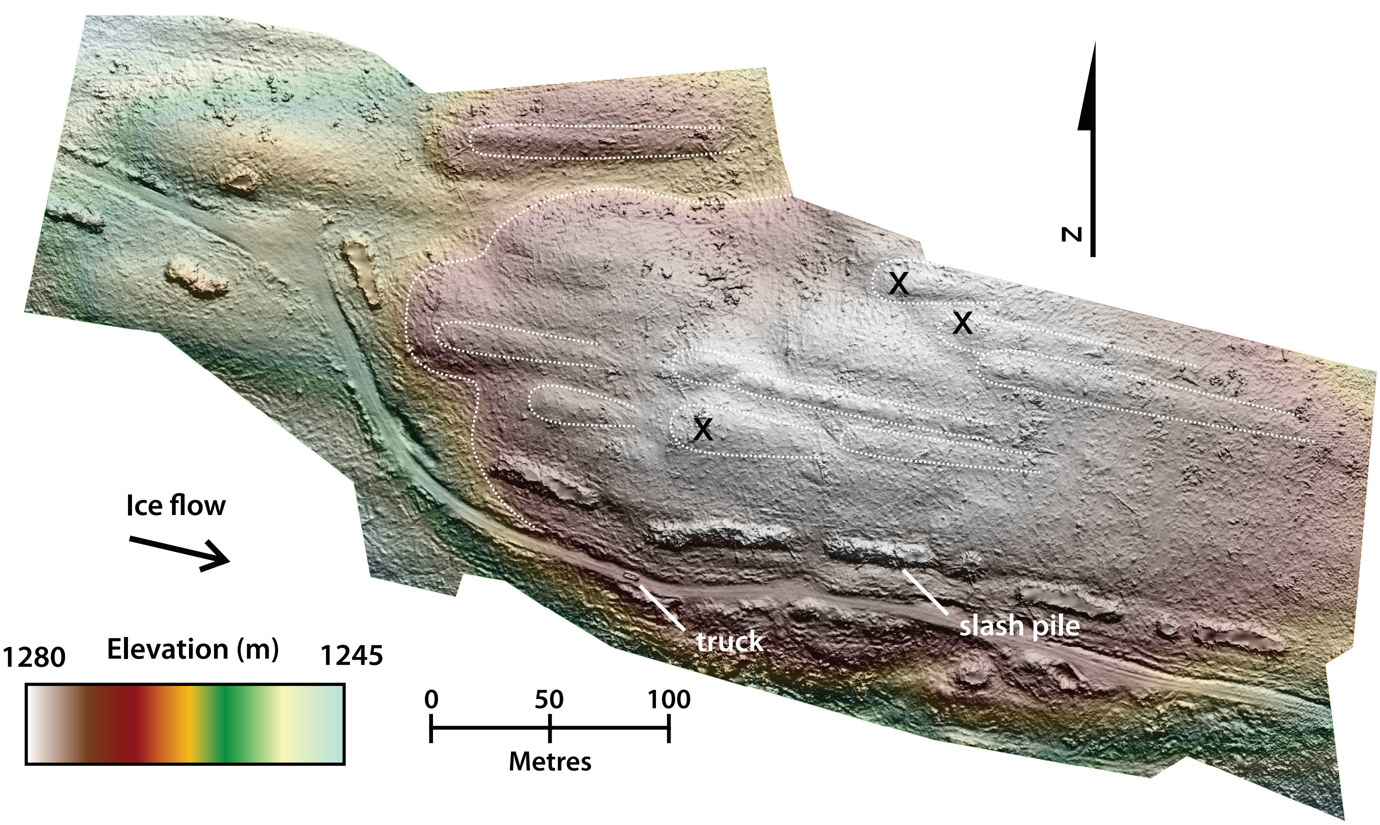

Fig. 8. Photogrammetric DEM of glacially streamlined terrain created from RPAS-acquired air photos. Outlined crag and tail features indicate ice flow towards the east-southeast. Bedrock outcrops represented by xs. See Figure 1 for location.

6. Discussion

6.1. Surficial geology and bedrock mapping

Remotely piloted aircraft system (RPAS) imagery, and derived photogrammetric digital elevation models (DEM), occupy a resolution between traditional, smaller-scale air photos and ground observations. Practical hardware design limitations (e.g., battery capacity) and flight regulations (altitude above ground; within visual line-of-sight; and others, see below) mean that at present RPAS cannot cover the same large areas that a piloted fixed-wing aircraft can. However, RPAS missions can be planned spontaneously to take advantage of exposure or access opportunities presented in the field. A high resolution (<10 cm/pixel), vertical perspective, photogrammetric DEM for sparsely vegetated to unvegetated terrain provides surficial geology mappers with additional context, or detail, on surficial material types and their surface expression. This is particularly true for areas where traditional datasets are lacking, and for newly logged or fire-burned areas where trees and vegetation have been removed.

The two RPAS missions presented here demonstrate how traditional fieldwork can be expanded. The photogrammetric DEMs changed how we mapped the survey areas. They also provide insight into glacial processes. For example, the survey over glacially streamlined terrain documented the eastward movement of the glaciers through the area during the Late Wisconsinan. This has immediate applications because, knowing ice-flow direction is key to finding the bedrock source of tills anomalous in commodity element concentrations or mineral grain counts (Levson, 2001). For the survey conducted over the hummocky terrain, differentiating between stagnant ice versus fluvial deposition can help predict aggregate quality. Although both surficial material types have high aggregate potential, the channelized areas are more likely to be composed of better sorted sands and gravels with lower silt-clay content; material appropriate for a gravel road running surface (Smith et al., 2005).

The same RPAS air photo methods used to map surficial geology can also be used to map bedrock lithology and structure (Nesbit et al., 2018). These systematic surveys, the acquired images, and derived geometrically rectified orthomosaics and DEMs, provide bedrock geologists perspectives that are difficult to obtain in the field, particularly in high-relief terrain. High-resolution orthoimages can be created within hours of completing an RPAS air photo survey and geologists can map directly onto these images using a standard field tablet. An RPAS survey was flown west of Hogem batholith, over a ridge consisting of rhyolitic tuffs and lesser andesite-basalt of the Asitka Group (Permian). The rhyolites weather maroon (oxidized) and white (reduced) and the andesite-basalt is darker green-black. The resultant colour orthomosaic has a resolution of 2.9 cm/pixel and oxidized (maroon) versus reduced (buff white) rhyolites can be identified on the northwestern cliff face (Fig. 9).

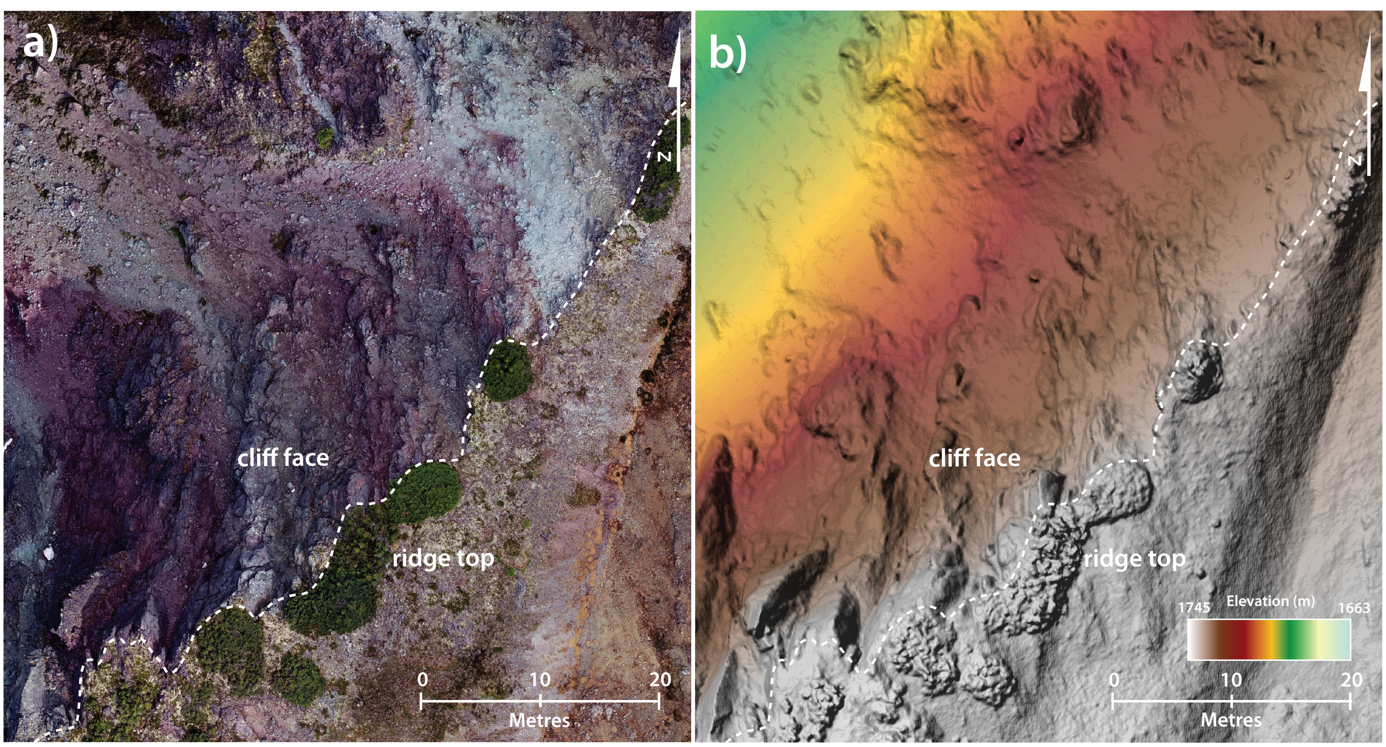

Fig. 9. a) Orthomosaic of bedrock ridge created from RPAS-acquired air photos. It is possible to identify and differentiate oxidized maroon rhyolites and reduced buff-white rhyolites on the northwestern cliff face. This orthomosaic is high-resolution (~3 cm/pixel) and can be used as a base map for fine-scale geologic mapping. **b)** Photogrammetric DEM produced for the same region. For general location see Figure 1, for specific location and perspective, see Figure 4.

6.2. Challenges

Jordan (2015) categorized the challenges of using RPAs in geoscience into natural, technological, and legal groupings; we experienced examples of each. The most significant natural challenge we encountered was tree cover. Tree canopies add noise and decrease resolution of photogrammetric DEMs and can also prevent visual line-of-sight between pilot and RPA. Precipitation and wind also proved challenging. All RPA have a wind speed resistance rating (DJI Phantom 4 Pro RTK is 10 m/s). Exceeding this rating will deplete batteries faster as the RPA works harder to maintain stability or a heading and can result in loss of RPA control. Some of our air photo missions had to be temporarily postponed due to wind or rain. The autopilot function in DJI GS RTK flight planning software made this easy to deal with. The survey can be paused and, once the poor weather passes, the mission can be invoked again and the RPA resumes the exactly where it left off.

A significant technology challenge to our survey was the need to log into DJI servers every 10 days to use the flight-planning software. We were unaware of this requirement until fieldwork began and, because our remote location, we had no internet access. Thus, the RPA was unflyable until a successful login was completed. Another technology challenge, inherent to all RPAS, is field repairs. Simple repairs like propeller replacement are straightforward and can be done in the field, but most other repairs require expensive replacement parts on hand and a clean workspace protected from weather.

In Canada and many other countries, regulations exist governing the registration of RPAS, certification of RPAS pilots, and where RPA can be flown given its weight, mission, and airspace classifications. Most existing literature regarding RPAS survey techniques and workflows unintentionally violate current Transport Canada regulations and cannot be directly followed. Current regulations should be reviewed and understood, in the context of a given application, before an RPAS is purchased. Some regulations can affect how a survey is conducted or dictate if it can be run at all.

6.3. The future?

Exchangeable-payload RPAS are the future for baseline and exploration geoscience applications. Today, RPAS-ready lidar, gamma ray spectrometers, magnetometers, hyperspectral, and VLF sensors are commercially available, with synthetic aperture radar expected soon. Each of these sensors could be used to infill, at an intermediate-scale, between traditional aerial and ground-based surveys, just as RPAS photogrammetric DEMs have. Although these sensors are expensive, some can be rented and fit on an RPAS system. Along with the instrument, software for each application needs to be considered prior to purchase. Not only does the ability to change payloads provide more versatility to the types of data the aircraft can collect, it also ‘future-proofs’ an RPAS program. Miniaturization of sensors and improvements to RPASs is being driven by advances in technology, and an exchangeable-payload approach is modular. Aircrafts or sensors can be switched in and out of an RPAS program so that updated technology can be incorporated when necessary.

7. Conclusion

We completed 16 RPAS air photo surveys in the Hogem batholith area using a DJI Phantom Pro 4 RTK. The RPAS acquired air photos automatically, following survey parameters set in DJI GS RTK flight-planning software. A dense point cloud and photogrammetric DEM were produced in the field for each survey area. The surveys were flown in areas with sparse vegetation, where high-resolution (<10 cm/pixel) photogrammetric DEMs rival lidar DEMs, gaining detail and insight on surficial materials and their morphology. Field-generated photogrammetric DEMs, produced in near real time, extended traditional point-based field observations (e.g., conducted at a road cut or soil pit) to observations of areas up to ~0.5 km^2. These observations improved our understanding of the surficial geology of the Hogem batholith area, resulting in more accurate mapping. They also helped guide the field program by providing insight and detail that otherwise could not be gained.

Exchangeable payload RPASs, and commercially available geophysical and imaging sensors further broaden the application of RPAS in geoscience. As with RPAS photogrammetric surveys, these sensors fill a niche between the scale of traditional airborne surveys (e.g., aeromagnetic) and outcrop-scale measurements (e.g., magnetic susceptibility). The miniaturization of traditional airborne sensors to a size that is RPAS mountable is technology driven. Many sensors like gamma ray spectrometers, VLF, hyperspectral, lidar are already commercially available. Others like electromagnetic sensors currently are not available but are likely to be so soon.

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