MODELING STRATIGRAPHIC ARCHITECTURE USING SMALL UNMANNED AERIAL SYSTEMS AND PHOTOGRAMMETRY: EXAMPLES FROM THE MIOCENE EAST COAST BASIN, NEW ZEALAND

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ABSTRACT

The ability to view and characterize outcrops that are difficult to study from the ground is greatly improved by aerial investigation. We describe the application of flying a small, unmanned aerial system (UAS) to collect photographic data for modeling rock outcrops and creating detailed digital elevation models (DEM), which can be used for mapping, measuring, and classroom education. High-resolution photographs acquired at various elevations and azimuths by a small UAS are used to convert field measurements to digital representations in three-dimensions at a fine scale. Structure from Motion (SfM) photogrammetry software is used to capture complex topography by creating digital surface models with a range imaging technique that estimates three-dimensional structures from two-dimensional image sequences. The digital surface model is overlain by detailed, high-resolution photography for fine-scale stratigraphic interpretation. The method of imaging and modeling remote outcrops is demonstrated in the East Coast Basin, New Zealand, where steep coastal cliff exposures of continental slope deposits and extensive wave-cut platform exposures of steeply-dipping deep-water basin deposits offer a unique opportunity to investigate flow processes and resulting stratigraphic architecture of each of these depositional environments. Our approach makes it possible to characterize East Coast Basin strata that are exposed in inaccessible, vertical sea cliffs and along 2,000 meters of wave-cut platforms, at centimeter-scale and to quantify geometric and spatial variation of each of these systems. Results yield a spatial and temporal understanding of two depositional systems at a scale that was previously unattainable using conventional field geology techniques.
INTRODUCTION

The increased sophistication and availability of unmanned aerial system (UAS) technology over the last decade provides a novel tool that has application to a wide range of scientific research. Studies of geohazard assessment and mitigation, geomorphology, geologic and structural mapping, ecosystem structure, and archaeological site monitoring have utilized UASs to augment conventional field practices (e.g., Niethammer et. al., 2011; Rinaudo et al., 2012; Bemis et al., 2014; Gauthier et al., 2014; Vasuki et al., 2014; Puttock et al., 2015). With respect to geologic studies, small UASs are particularly useful for overcoming two challenges: 1) investigating and visualizing outcrops that are otherwise inaccessible due to physical constraints (e.g., steep cliff or deep ravine exposures); or 2) gaining a high vantage point to visualize steeply dipping stratigraphy exposed within low topographic relief.

Pairing small UAS technology with readily available photogrammetry software that requires little processing time and resources offers a revolutionary and cost-effective methodology for geoscientists to investigate and quantify stratigraphic and structural complexity of a variety of field studies (Hackney and Clayton, 2015; Micheletti et al., 2015). Much as laser ranging and light imaging detection ranging (LiDAR) surveys revolutionized the collection of spatially accurate geologic data (Bellian et al., 2005), the pairing of a small UAS and photogrammetry provides a more practical, low-budget, and equally effective method of remote sensing. Whereas traditional LiDAR surveys are labor-intensive, expensive, and require specialized, manned aircrafts to obtain aerial perspectives, small UASs allow the user to obtain results of comparable quality in shorter time and at lower cost. Furthermore, combining user-friendly photogrammetry software with high-resolution images captured by a UAS makes it possible to create a spatially correct, three-dimensional (3-D) virtual outcrop of even the most inaccessible rock exposures in a fraction of the time it would take using other techniques (Tavani et al., 2014).

This work illustrates the effectiveness of using a small consumer-grade UAS paired with photogrammetry software for stratigraphic interpretation. Two examples of using small UASs to overcome challenges of viewing and accessing outcrop exposures are demonstrated at Mahia Peninsula, North Island of New Zealand (Fig. 1). This methodology facilitates interpretation of vertical and lateral variation of lithofacies and larger-scale stratigraphic and structural architecture of sandstone bodies over outcrop areas that would otherwise prove difficult to study.
using only traditional methods. Detailed investigation of such exposures is best addressed by pairing modeling software with imagery acquired by a small UAS that can safely navigate from high-altitude overviews of study areas to within a meter of the exposure of interest.

STUDY AREA

The East Coast Basin, located along the east coast of New Zealand, is presently in an active forearc setting. Miocene to modern sediments record a complex history of Neogene forearc evolution. Although roughly half of the modern East Coast Basin lies offshore, Neogene deposits are exceptionally well exposed in coastal cliffs and wave-cut platforms along the entire coast of the North Island. This work focuses on stratigraphic architecture of two separate outcrops that each present challenges in accessibility: 1) upper Miocene slope deposits exposed in coastal cliffs along western Mahia Peninsula (Fig. 1A, B; Francis, 1993: Chanier et al., 1999); and 2) middle Miocene thin-bedded turbidites exposed along eastern wave-cut platforms of Mahia Peninsula (Fig. 1C, D; Francis, 1993; Timbrell, 2003).

DATA ACQUISITION AND PROCESSING

Aerial photographs were acquired using an affordable, consumer-grade quadcopter that is portable and maneuverable. Specifically, the small UAS used was the DJI Phantom 2 Vision+ model, with a mounted high-resolution (14 megapixel) camera that can tilt from near 0 to -90° to best capture exposure geometry and bedding dip. Depending on the resolution required, images were acquired from elevations ranging from 2 to 90 meters above the outcrop exposure surface. A minimum of three ground control points and a scale were included in each area that was photographed (Fig. 2A). These images were acquired with 40-60% overlap in order to maintain continuity of the model. The small UAS was flown over each outcrop in several passes and at multiple azimuths (i.e., not only in line with bedding) to fully characterize topographic variations, as it is important to capture key features from at least two angles in order to generate an accurate 3-D model (Fig. 2B).

Commercial photogrammetry software ‘PhotoScan Professional Edition’ by Agisoft was used to incorporate visuals captured by the small UAS and create digital surface models (Westoby et al., 2012). A standard workflow described by Westoby et al. (2012) was followed and is summarized: 1) sparse point cloud is created from key corresponding points identified in
overlapping photos (Fig. 2C), 2) triangulation is used to estimate 3-D point positions and incrementally estimate scene geometry, 3) dense point cloud is created (Fig. 2D), a mesh is made (Fig. 2E), and a final textured 3-D surface is reconstructed (Fig. 2F), and 4) the final digital outcrop model is created (Fig. 2G). Interpretations can be made directly on the generated 3-D model or orthophotographs can be derived for spatially-correct 2-D stratigraphic representation (Fig. 2H). Ground GPS coordinates taken in the field were input into each digital elevation model (DEM) created to render a georeferenced spatially accurate model.

MODELS

Western Mahia Peninsula: structurally complex beds exposed in vertical cliff faces

Cliff exposures of middle Miocene slope deposits exposed along the western coast of Mahia Peninsula (Fig. 1; Fig. 3) present contrasting challenges from those on the eastern side of the peninsula. These coastal cliffs have greater than 150 m of vertical relief that is too steep and unconsolidated to access (Fig. 1A) and the base of the cliffs are only partially accessible via a narrow platform that is above sea level only during low tide (Fig. 1B). Exposed stratigraphy is highly deformed, and complex faulting occurs throughout the section.

Flying a small UAS along the faces of these cliffs made it possible to fully document the exposed structure and stratigraphy at a scale necessary for stratigraphic interpretation. Imagery collected by the UAS documents the outcrop at resolutions and perspectives that cannot otherwise be achieved on the ground or from a boat (Fig. 1B). Combining these images with photogrammetry makes it possible to interpret features that cannot be documented in any other way because of inaccessibility (Fig. 3).

Each of three cliff exposures along the western side of Mahia Peninsula (Fig. 1A, B) was flown and modeled. For each model, the UAS was flown approximately 15 m away from the cliff face (Fig. 3). Select deformation features were chosen to document at higher resolution, for which the UAS was flown as close at 5 m from the cliff face (Fig. 3A, B). With the spatially accurate models that were produced with photogrammetry, various syn-depositional deformation features (Fig. 3A), faults, and other structural features (Fig. 3B) can be can be mapped and measured in two and three dimensions.

Models generated with imagery of all three cliff exposures document what we interpret to be syndepositional faulting recording headwall extension to footwall thrusting of slope deposits.
above a detachment surface that overlies undeformed stratigraphy. Centimeter-scale models document listric normal faulting and a rollover anticline above the detachment surface in addition to drag folding (Fig. 3B). Meter-scale soft sediment deformational features higher up in stratigraphy are interpreted as mass failure deposits (Fig. 3A), likely related to syndepositional faulting of the underlying stratigraphy.

**Eastern Mahia Peninsula: steeply-dipping beds exposed on a wave-cut platform**

Characterizing the stratigraphic architecture of steeply-dipping deep-water deposits exposed on wave-cut platforms along the east coast of Mahia Peninsula (Fig. 1C, D) is challenging due to exposures that are difficult to view at an architectural scale from the ground. The strike exposure of these thin-bedded turbidites extends over 2 km and offers a unique opportunity to investigate lateral variations of deep-water systems. However, due to bedding dips of approximately 50° and low topographic gradient of the outcrop exposure, beds can only be viewed laterally for a few tens of meters from the ground (Fig. 1C) and correlation by traditional field methods alone requires physically walking out every bed. Furthermore, investigation is hindered by a high tide cycle that completely covers the wave-cut platform twice a day and only allows a maximum six-hour window to correlate and characterize beds.

The use of a small UAS offered an efficient and effective solution for overcoming these challenges of characterizing the entire wave-cut platform extent of middle Miocene thin-bedded turbidites. The UAS provided vantage points at altitudes high enough above the exposures to view the steeply-dipping beds and obtain photographic documentation of the entire lateral exposure (>2 km). Pairing the UAS imagery with the photogrammetry workflow produced models that could be investigated during hours when high tide limited access to the study area (Fig. 4). Depending on the height at which the UAS was flown above the exposure, stratigraphic detail could be obtained at various resolutions. Images acquired at lower heights (closer to the exposure) yielded higher resolution models of the outcrop; however, more images and thus larger quantities of data were required to cover the same area as images taken from greater heights.

The thin-bedded turbidites at Mahia Peninsula were modeled at two different scales in order to illuminate their depositional framework: 1) the UAS was flown at approximately 2m above the exposure to acquire centimeter-scale resolution where detailed stratigraphic sections were measured in order to investigate the variations in depositional flow processes; and 2) the
UAS was flown greater than 30m above the entire wave-cut platform exposure to acquire decimeter-scale resolution to investigate lateral variability of beds over several meters to over a kilometer (Fig. 4).

Seven detailed stratigraphic sections that were measured in the field were geospatially tied to the eastern Mahia Peninsula models. Depositional geometries (Fig. 4A) were observed and mapped on resulting models. Where centimeter-scale resolution data was acquired, bed lithologies and sedimentary structures that were characterized in detailed measured sections were matched to the model and laterally mapped over short distances (Fig. 4B). In addition, sandstone beds identified in the seven stratigraphic sections were laterally correlated over kilometers throughout the entire model, including sections that underwent minor faulting. Correlations were independently checked in the field using an orthophotograph that was exported from the model. The resulting interpreted digital outcrop model allows for thickness variations and lateral extent of the thin-bedded turbidites to be spatially analyzed.

**DISCUSSION**

We demonstrate the effectiveness of pairing photogrammetry with high-resolution imagery collected by a small UAS to model and study both fine-scale stratigraphy and large-scale stratigraphic architecture, particularly in remote or inaccessible outcrop locations. Models render spatially correct, 3-D digital representations of the outcrops. At the most inaccessible rock exposures, these models can aid in making observations that cannot otherwise be made with conventional ground-based field geology techniques. When paired with field-collected data, generated models can enhance measurements made in the field.

Taking advantage of well-exposed outcrops to map and study deposits, such as those exposed at western Mahia Peninsula, is integral to our better understanding of depositional systems, their flow processes, and their resulting geometries. Continental slope deposits and large mass failures are poorly represented in outcrop. Even where rock exposures exist, such deposits are commonly challenging to study due to discontinuous, interrupted bedding and structural complexity. The cliffs at western Mahia Peninsula offer a world-class exposure of slope failure deposits that can be accurately measured on photogrammetry models built with images acquired by a small UAS. Understanding thin-bedded turbidites is important because fine-grained, thin-bedded deep-water deposits have proven to be important hydrocarbon
reservoirs if they are laterally continuous and vertically stacked (DeVries and Lindholm, 1994; Shew et al., 1994; Bramlett and Craig, 2002). Stratigraphic architecture of thin-bedded turbidites is closely tied to reliable interpretation of depositional environment (i.e., distal lobe or channel-levee deposits). Because thin-bedded deposits cannot be sufficiently imaged in seismic reflection data, the only opportunity to study their architecture and bed character is with core and outcrop studies. Photogrammetry models of the immense lateral exposure of thin-bedded turbidites along eastern Mahia Peninsula allow characterization of bed thickness, type, and connectivity to be presented in a manner that can be useful for reservoir prediction and production modeling. Data presented in the context of the system’s depositional environment provides an analog for reservoirs of stacked thin beds in similar basin settings.

Small UASs have been implemented in a variety of geomorphic, structural, and natural hazard studies over the past few years (e.g., Micklethwaite et al., 2012; Carrivick et al., 2013; Marris, 2013; Tavani et al., 2014). Likewise, digital outcrop models created by conventional acquisition methods (i.e., LiDAR) have been used for stratigraphic studies interpretation for over a decade (e.g., Tomasso et al., 2006; Bonnaffe et al., 2007; Rarity et al., 2014). The maneuverability of small UASs allows them to photograph outcrops that are otherwise unreachable from the ground, and in some cases even from the air, if flying anything larger than a small UAS. We demonstrate that pairing modeling software with aerial imagery collected by small UASs can significantly strengthen stratigraphic interpretation and generate digital outcrop models comparable to those generated with conventional acquisition methods. However, unlike LiDAR acquisition and processing, which require significant investment of resources for each survey, this study presents an affordable and efficient methodology that only requires an initial investment for the UAS and professional photogrammetry tools. The growing technology behind UASs make them easy to acquire and maneuver, and although commercial software Agisoft PhotoScan was used for this work, there are many open source photogrammetry programs available at no cost. The affordability and availability of small UASs and a variety of photogrammetry programs makes this methodology very accessible for research and also for teachers to create models for classroom education.

Some limitations related to the use of UAS technology include: 1) the inherent risk of flying in wind or poor weather; 2) current flight time of each flight and the limiting factor often being the number of batteries available in the field; 3) enforced height restrictions for all UASs;
and 4) continually increasing legislation on the use of UAS technology. The small UAS used for this work was capable of flying in up to 30 km/hr winds with a slightly shorter battery life in such weather. On average, the UASs we used had 20-25-minute flights per battery. Legislation on the operation of UASs is one of the largest impediments to advancing this methodology as a standard procedure for interpreting complex stratigraphic architecture in outcrop exposures. Just as the ethics of fieldwork must be considered with conducting fieldwork on public or private land, similar cautions must be taken when flying UASs. Where outcrops are more accessible, photogrammetry software can be used with ground-based images, as well. The use of a ground-based, higher resolution camera can render higher-resolution models. The use of UASs helps most when trying to document otherwise inaccessible outcrops.

Two case studies provide examples for which this method is particularly useful: 1) investigating outcrops exposed in steep cliffs that are otherwise inaccessible, and 2) gaining a high vantage point to visualize steeply dipping stratigraphy exposed by wave-cut platforms. For each of these examples, a wide range of resolution can be obtained, depending on if the UAS is flown for a high-altitude overview or within meters of the exposure. Given the effectiveness of using a small UAS and the manageable amount of processing required by most photogrammetry programs to create a semi-automated model, it is possible to generate a high-resolution DEM, or outcrop model, the same day that the imagery is obtained on the outcrop itself.

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REFERENCES


Figure 1. Location of study areas at Mahia Peninsula, North Island, New Zealand. A,B: Western Mahia Peninsula cliff exposures of late Miocene slope deposits seen from the water (A) and the air with an unmanned aerial system (B). C,D: Eastern Mahia Peninsula wave-cut platform exposure of middle Miocene thin-bedded turbidites photographed from the ground (C) and from the air (D).
Figure 2. Workflow outlining methodology of combining field data and imagery (A,B) collected by an unmanned aerial system (UAS), with photogrammetry software Photoscan Pro by Agisoft, whose standard workflow (C-G) is described by Westoby et al. (2012), resulting in interpretive models (H). A: Stratigraphic sections (S1-S4) are measured in the field and a minimum of three ground GPS locations (P1-P3) are taken as control points. B: Small UAS is flown over the outcrop exposure at various elevations and azimuths, acquiring images (e.g. rectangles 1-4 in figure) from different angles and with 40-60% overlap. C-G: Images and ground control points are input into photogrammetry software (see Westoby et al, 2012) that sequentially builds final 3-D outcrop model (G). H: Georeferenced spatially accurate outcrop model is used for further interpretation and/or detailed mapping of exposure.
Figure 3. Digital outcrop model of the southernmost cliff exposure along western Mahia Peninsula. Images used for depicted model were acquired by flying UAS 15 m away from exposure. A: Syndepositional deformation recorded in slope failure deposits. B: Drag folding related to syndepositional faulting.
Figure 4. Digital outcrop model of wave-cut platform exposure along eastern Mahia Peninsula. Images used for depicted model were acquired by flying UAS 30 m above exposure. A: Nested scour surfaces observed from the air. B: High-resolution portions of model (from images acquired 2 m above outcrop exposure) matched to cm-scale stratigraphic sections measured in the field.