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Integrating airborne hyperspectral imagery and LiDAR for volcano mapping and monitoring through image classification

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ABSTRACT

Optical and laser remote sensing provide resources for monitoring volcanic activity and surface hydrothermal alteration. In particular, multispectral and hyperspectral imaging can be used for detecting lithologies and mineral alterations on the surface of actively degassing volcanoes. This paper proposes a novel workflow to integrate existing optical and laser remote sensing data for geological mapping after the 2012 Te Maari eruptions (Tongariro Volcanic Complex, New Zealand). The image classification is based on layer-stacking of image features (optical and textural) generated from high-resolution airborne hyperspectral imagery, Light Detection and Ranging data (LiDAR) derived terrain models, and aerial photography. The images were classified using a Random Forest algorithm where input images were added from multiple sensors. Maximum image classification accuracy (overall accuracy = 85%) was achieved by adding textural information (e.g. mean, homogeneity and entropy) to the hyperspectral and LiDAR data. This workflow returned a total surface alteration area of ~0.4 km^2 at Te Maari, which was confirmed by field work, lab-spectroscopy and backscatter electron imaging. Hydrothermal alteration on volcanoes forms precipitation crusts on the surface that can mislead image classification. Therefore, we also applied spectral matching algorithms to discriminate between fresh, crust altered, and completely altered volcanic rocks. This workflow confidently recognized areas with only surface alteration, establishing a new tool for mapping structurally controlled hydrothermal alteration, evolving debris flow and hydrothermal eruption hazards. We show that data fusion of remotely sensed data can be automated to map volcanoes and significantly benefit the understanding of volcanic processes and their hazards.

1. Introduction

The complexity of long-lived volcanic systems may be lost in remote sensing-derived geological maps that only consider topographic information. Hence, considering additional information (e.g. spectral data) in surface mapping can improve the recognition of landforms and surface processes unique to volcanic terrains (e.g. Kruse, 2012).

Imaging spectroscopy, or hyperspectral imaging, measures reflected, absorbed and emitted light of objects at many narrow and contiguous wavelengths in the Visible and Near-Infrared (VNIR; 350–1000 nm) and Shortwave Infrared regions (SWIR; 1000–2500 nm) (Goetz et al., 1985; Vane et al., 1993; Plaza et al., 2009). Space and airborne hyperspectral sensors, such as Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), Reflective Optics System Imaging Spectrometer (ROSIS), Compact Airborne Spectrographic Imager (CASI), Hyperion on the EO-1 satellite, HyMAP, Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) and Specim AisaFENIX, are among the most commonly used hyperspectral sensors (Kunkel et al., 1991; Chen et al., 1999; Hellman and Ramsey, 2004; Forzieri et al., 2013; Hosseinjani Zadeh et al., 2014; Magendran and Sanjeevi, 2014; Swayze et al., 2014; Huesca et al., 2016; Pullanagari et al., 2016; Sun et al., 2016; Feng et al., 2018).

Geological mapping and mineral exploration can benefit from hyperspectral imaging due to indicator minerals with characteristic absorption features in the VNIR and SWIR regions of the electromagnetic spectrum (Clark, 1999; van der Meer, 2018; Carrino et al., 2018; Liu et al., 2018). In the VNIR region, the most detectable changes are due to the transfer of electrons between the atomic energy levels in elements such as iron (Fe^{2+} and Fe^{3+}), manganese (Mn), nickel (Ni) and chromium (Cr). Thus, the VNIR region is particularly useful for detecting

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minerals such as hematite (Fe_2O_3), goethite (FeO(OH)) and jarosite ($KFe_3^{3+}(OH)_6(SO_4)_2$) (Kruse et al., 1993; Clark, 1999; Murphy and Monteiro, 2013; Magendran and Sanjeevi, 2014; van der Meer, 2018; De Boissieu et al., 2018). The SWIR region provides a proxy for detecting vibrational features of Al − OH, Mg − OH, C−O-bearing minerals such as sulphates, carbonates, micas, and clay minerals. The presence of the latter is an indicator of hydrothermal alteration, or change in mineralogy as a result of hot water interacting with the rocks, and ore mineralization (Kruse et al., 1993; Crowley et al., 2003b; Kruse et al., 2012; Swayze et al., 2014). The use of hyperspectral remote sensing for surface geological mapping and mineral alteration detection has been employed mostly in exploration geology using Hyperion, HyMAP and AVIRIS data (e.g. Bedini et al., 2009; Magendran and Sanjeevi, 2014), and spectral matched linear filtering methods (Kruse et al., 1993; Boardman et al., 1995; Rogge et al., 2014).

For volcano and geothermal research, Landsat series and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) have been used extensively (Pieri and Abrams, 2004; Vaughan et al., 2005; Mia and Fujimitsu, 2012; Tayebi et al., 2014; van der Meer et al., 2014). Moreover, a great variety of research has been published using Light Detection and Ranging (LiDAR) technology to explore volcanic terrains and volcano-related hazards (Spinetti et al., 2009; Kereszturi et al., 2012; Tarquini et al., 2012; Whelley et al., 2014; Behncke et al., 2016). In contrast, hyperspectral imagery has rarely been employed for volcano geological mapping. These include mineral alteration mapping using spectral matched linear filtering methods (e.g. Boardman et al., 1995), such as at the Mauna Kea volcano in Hawaii (Guinness et al., 2007), and Mt. Shasta and Mt. Rainier volcanoes in the western USA (Crowley and Zimbelman, 1997; Crowley et al., 2003a). Other studies have used hyperspectral imagery to estimate CO_2 concentrations in volcanic plumes at Kilauea in Hawaii (Spinetti et al., 2008), map thermal structure of an active lava flow on Mt Etna in Italy (Lombardo et al., 2009), and create geological maps of Hekla volcano in Iceland (Waske et al., 2009). Spectral information combined with the recent developments in statistical learning for image classification and regression (e.g. Mountrakis et al., 2011; Cracknell and Reading, 2014; Pullanagari et al., 2016; Toniol et al., 2017) can provide insights for geological applications with importance to understanding complex volcanic systems, volcanic hazards, and geothermal resources.

This paper combines airborne hyperspectral data, high-resolution optical imagery, and Light Detection and Ranging (LiDAR) topographic data to map and identify volcanic deposits based on spectral and textural signatures. The developed workflow uses pixel-wise image stacking and image classification to provide an updated surface geological map after the 2012 eruptions of the Te Maari craters, Tongariro Volcanic Complex, New Zealand (Fig. 1A and B). In 2012, Te Maari craters produced two phreatic eruptions, one of which was landslide-triggered highlighting the need to study hydrothermal alteration on volcanoes using a combination of field, analytical and remote sensing techniques. Hence, the present study aims to provide a surface mapping workflow that can be integrated into volcanic hazard assessments (e.g. hydrothermal alteration mapping, delimitation of potential debris flow source zones) and efforts to understand volcanic processes (e.g. identification of sediment transport processes).

2. Study area, materials and data processing

2.1. Geological setting

The Tongariro Volcanic Centre is located in the southern extremity of the Taupo Volcanic Zone, formed in a back-arc setting due to an oblique westward subduction of the Pacific Plate beneath the Australian Plate (Houghton et al., 1995; Wilson et al., 1995). The volcanic zone is dominated by NE-SW-oriented normal faulting of the Taupo rift system that is dominated by extension and high heat flux (Bibby et al., 1995; Villamor and Berryman, 2006; Gómez-Vasconcelos et al., 2016). The basement around the Tongariro volcanic complex is made of the Mesozoic Torlesse Terrain and Waipapa Terrane units that is mostly comprised of greywacke (Townsend et al., 2017). These units are overlain by Cenozoic marine sedimentary rocks and Quaternary lava and volcaniclastic rocks (Townsend et al., 2017).

Volcanism at the Tongariro Volcanic Centre has developed an elongated NE-SW vent zone roughly 14 km long by 5 km wide. This vent zone has at least 15 highly overlapped individual cones each with a volume of $> 0.5\,km^3$ that show no spatial and temporal trend over the last 275 ky (Hobden et al., 1996; Nairn et al., 1998; Hobden et al., 1999). Volcanic activity at the Tongariro Volcanic Centre is characterised by frequent, small-volume eruptions (0.1-1 km^3), forming a highly coalescent and dissected volcanic complex. The erupted magmas have intermediate compositions spanning from basaltic-andesite to dacite (Nakagawa et al., 1998; Hobden et al., 2002; Shane et al., 2017). Most eruptions in the post-glacial era have erupted from multiple vents located around the Te Maari craters and Red Crater (Scott and Potter, 2014; Miller and Williams-Jones, 2016).

The most recent eruptions occurred at the upper Te Maari crater on the 6^{th} August and 21^{st} November 2012 (Fig. 1A and B). These short-lived eruptions (< 1 min) deposited a thin veneer of ash over an area of 1600 km^2 (Pardo et al., 2014; Turner et al., 2014). The August eruption was triggered due to decompression of the hydrothermal system after a seismically-induced landslide uncapped ca. $7 \times 10^6\,m^3$ of material from the northern flanks (Jolly et al., 2014; Pardo et al., 2014; Procter et al., 2014). The landslide evolved into a debris flow that traveled for 2 km, covering the upper catchment of the Mangatipua stream with a mixture of hydrothermally altered breccia, agglutinated scoria and spatter deposits in a clay-rich matrix (Fig. 1B). The host rock of the landslide was a moderate to highly altered agglutinated and welded to non-welded scoriaceous deposits from the Blue Lake Crater. These welded scoriaceous deposits forms from mechanical compaction of the fluidal particles after deposition, while agglutination is a heat-driven sticking of particles together (e.g. Sumner et al., 2005). The eruption produced multiple lateral blasts and an eruption column as high as 10 km (Pardo et al., 2014; Turner et al., 2014; Montanaro et al., 2016). Evidence suggests that the landslide slip surface occurred through a highly altered scoriaceous pyroclastic deposit (Procter et al., 2014). This hazard scenario had not been foreseen based on the preserved geological record. However, areas of pervasive hydrothermal alteration are known to exist in the Tongariro Volcanic Complex that are generally produced due to circulation of hydrothermal fluids through the various edifices (Brock and Brock, 1971; Miller and Williams-Jones, 2016; Miller et al., 2018). One prominent area is the Ketetahi Springs, which has numerous fumaroles, mud pools and hot springs that precipitate iron hydroxides and sulphur (Brock and Brock, 1971; Moore and Brock, 1981). The ongoing alteration around the Ketetahi and Te Maari areas weakens volcanic rocks and deposits, posing potential hazards to both population (e.g. hikers along the frequently visited Tongariro Alpine Crossing Track) and critical infrastructure (e.g. State Highway 46).

2.2. Instrumentation, aerial-surveys and image processing

The airborne hyperspectral survey was carried out at Tongariro Volcanic Centre between 12:25 and 13:43 local time on the 7 April 2016 (UTC + 12 h) with a push-broom, full-spectrum AisaFENIX hyperspectral sensor (370–2500 nm). The spectral sampling interval was between 3.3 and 5.7 nm from VNIR and SWIR region with a full-width-at-half-maximum of 3.2–12.2 nm. The AisaFENIX has a total Field of View of 32.2°, and an Instantaneous Field of View of 0.084°. The misalignment between the Oxford Survey + GPS/IMU unit and the AisaFENIX sensor was reduced by applying boresight corrections to the imagery, based on a calibration flight. The GPS/IMU data was post-processed to reach an accuracy under a pixel (< 2 m) using permanent ground GPS station data from stations closer than 50 km from a survey site. The swaths were orientated from N (170°–190°) and S (350°–10°)