Hydrothermal Alteration on Composite Volcanoes: Mineralogy, Hyperspectral Imaging, and Aeromagnetic Study of Mt Ruapehu, New Zealand

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Abstract Prolonged volcanic activity can induce surface weathering and hydrothermal alteration that is a primary control on edifice instability, posing a complex hazard with its challenges to accurately forecast and mitigate. This study uses a frequently active composite volcano, Mt Ruapehu, New Zealand, to develop a conceptual model of surface weathering and hydrothermal alteration applicable to long-lived composite volcanoes. The alteration on Mt Ruapehu was classified using ground samples as non-altered, supergene argillic, intermediate argillic, and advanced argillic. The first two classes have a paragenesis that is consistent with surficial infiltration and circulation of low-temperature (<40°C) neutral to mildly acidic fluids, inducing chemical weathering and formation of weathering rims on rock surfaces. The intermediate and advanced argillic alteration formed from hotter (≥100°C) hydrothermal fluids with lower pH, interacting with the andesitic to dacitic host rocks. The distribution of weathering and hydrothermal alteration has been mapped with airborne hyperspectral imaging through image classification, while aeromagnetic data inversion was used to map alteration to up to 500 m depth. The joint use of hyperspectral imaging complements the geophysical methods since it can spectrally identify hydrothermal alteration mineralogy. This study established a conceptual model of hydrothermal alteration history of Mt Ruapehu, exemplifying a long-lived and nested active and ancient hydrothermal system. This study’s combination approach can be used to indicate the most likely sources of future debris avalanches, which are a significant hazard on Ruapehu.

Plain Language Summary Groundwater heated by shallow molten rock and volcanic gases beneath a volcano can become acidic. When the acidic groundwater rises to the surface, it chemically interacts with volcanic rocks. This interaction turns the rocks and thus the volcano weaker (e.g., replacement of original mineralogy by softer clay minerals), making the edifice more susceptible to collapse. This study integrates geological, remote sensing and geophysical methods to understand the hydrothermal alteration history of Mt Ruapehu, New Zealand. The rock samples collected indicate different minerals associated with alteration processes due to acidic groundwater. Hyperspectral imaging, which measures reflected radiation from the Earth’s surface at hundreds of wavelengths, was used to map the distribution of the surface mineralogy using image classifications. The underground distribution of the weak rocks was identified using aeromagnetic surveys. Aeromagnetic data are sensitive to iron-bearing minerals that are often dissolved by hydrothermal fluids, leaving low magnetic anomalies distributed underground at Mt Ruapehu. Based on the combination of these methods, we propose a new conceptual model for the alteration history of Mt Ruapehu during the last 200,000 years, contributing to a fuller assessment of natural hazards associated with large-scale landslides.

1. Introduction

Interaction of the magmatic heat and gases (e.g., H2O, SO2, CO2, and Cl) drives infiltrating surface and groundwater to ascend through volcanic host rocks while leaching primary alkali (Na and K) and alkaline earth metals (Mg and Ca). This process can also replace existing mineral phases and precipitate new secondary minerals at shallower depths (Ganino et al., 2019; Hynek et al., 2013; Rowe & Brantley, 1993; Rye et al., 1992). Acid sulfate alteration forms typical intermediate and advanced argillic mineral assemblages,
including phyllosilicates (Dill, 2016; Hynek et al., 2013), sulfates (Rye et al., 1992; Zimbelman et al., 2005), sulfides, and native sulfur (Inostroza et al., 2020; Piochi et al., 2015). The majority of hydrothermal alteration occurs beneath the surface in hypogene conditions. However, mineral assemblages formed under hypogene conditions are often subject to supergene weathering and erosion which can replace some of the metastable hydrothermal minerals under atmospheric pressure and temperature conditions, including dickite, anhydrite, sulfur, and pyrite (Fernández-Caliani et al., 2004; John et al., 2008; Scott, 1990; Zimbelman et al., 2005).

This commonly results in mineral overprint, making interpretations of the original hydrothermal condition, fluid composition, and pH challenging, particularly on complex and long-lived volcanic systems.

Hydrothermal alteration changes rock mechanical and geotechnical properties (del Potro & Hürlimann, 2009; Pola et al., 2014), promoting flank instability (Finn et al., 2001; Heap et al., 2015; John et al., 2008; López & Williams, 1993; Norini et al., 2020; Schaefer et al., 2015) and decreasing permeability, which can lead to phreatic eruptions (Mayer et al., 2017; Pardo et al., 2014). Hydrothermal alteration primarily reduces rock strength (del Potro & Hürlimann, 2009; Farquharson et al., 2019) and changes permeability (e.g., mineral precipitation into pores and cracks which decreases permeability) within the volcanic edifice (Mordensky et al., 2019), which may locally elevate pore pressure promoting edifice flank instabilities (Ball et al., 2018; Collard et al., 2020; Reid, 2004). Flank instabilities and the resulting mass flow events triggered by gravity, weather events, volcanic eruptions, magmatic intrusions, and earthquakes (Capra, 2006; Procter et al., 2014; Schaefer et al., 2018) can result in far-reaching and potentially dangerous volcanic hazards downstream from volcanoes (Finn et al., 2001).

Geological mapping and quantification of hydrothermal alteration in volcanic systems have traditionally been carried out using ground and field geological mapping, combined with scanning electron microscopy (SEM), X-ray diffraction (XRD), and X-ray fluorescence (XRF), and isotope and fluid inclusions studies, among others, to constrain the paragenesis of the alteration mineral suites (Ball et al., 2013; Christenson & Wood, 1993; John et al., 2008; Nuñez-Hernández et al., 2020; Piochi et al., 2019; Rye, 2005; Zimbelman et al., 2005). Multispectral satellite remote sensing in the visible and near infrared (VNIR; 300–1,000 nm) and shortwave infrared (SWIR; 1,000–2,500 nm) is often used to upscale mapping efforts, using Landsat series (Mia & Fujimitsu, 2012; Wright et al., 2001), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; Chattoraj et al., 2020; Galvão et al., 2005), and WorldView (Kruse et al., 2015). Hyperspectral remote sensing is becoming a common tool for mineral alteration mapping, improving the differentiation among key indicator minerals such as alunite, jarosite, kaolinite, montmorillonite and illite, and mica, offering a cost-effective but highly sophisticated technological solution (Carrino et al., 2018; Crosta et al., 1998; Crowley et al., 2003; Hellman & Ramsey, 2004; Kereszturi et al., 2018; Swayze et al., 2014; van der Meer, 2004). However, optical remote sensing is limited to quantify only the surface manifestation of hydrothermal alteration and weathering, limiting inputs for a comprehensive hazard assessment of volcanic systems.

Complementing ground and remote sensing methods, geophysical techniques, including electromagnetic resistivity, gravity and aeromagnetic surveys (Finn et al., 2018; Miller & Williams-Jones, 2016), magnetotelluric surveys (Abdallah et al., 2020; Bowles-Martinez & Schultz, 2020; Jones et al., 2008; Matsunaga et al., 2020), seismicity (Pu et al., 2020), and muon imaging (le Gonidec et al., 2019), have also been used to infer internal architecture and locate hydrothermal fluids and zones of demagnetization of the host rock. These methods are often complemented with numerical methods (e.g., inversion) and spring and gas chemistry data to gain insights into the thermal and chemical evolution of shallow magmatic-hydrothermal systems (Berlo et al., 2020; Collard et al., 2020; Gresse et al., 2018; Miller et al., 2020). Therefore, geophysical inversion methods can add the depth component to quantify hydrothermal alteration processes and volumes of altered rock masses, contributing important inputs to mass flow initiation and run-out models and hazard assessment (Finn et al., 2001, 2018; Rosas-Carabajal et al., 2016).

Both geophysical and optical remote sensing approaches have been demonstrated to be useful for mapping hydrothermal alteration products. However, the joint use of such methods is seldomly presented on composite volcanoes to fingerprint hydrothermal alteration processes on the surface and depth. This study aims, therefore, to explore the hydrothermal alteration history of a long-lived and complex andesitic composite volcano, Mt Ruapehu, New Zealand, using a novel combination of mineralogical, hyperspectral, and geophysical imaging techniques. The detailed reconstruction of the hydrothermal alteration history and
A conceptual model can provide inputs to predict edifice instabilities and associated geophysical mass flow hazards around composite volcanoes.

2. Geological Setting

The southern part of the Taupo Volcanic Zone contains Mt Tongariro and Mt Ruapehu volcanoes and several smaller inactive volcanic centers, which collectively form the Tongariro volcanic complex (Figure 1a). Mt Ruapehu, 2,797 m a.s.l. and 110 km³, is a frequently active andesite-dacite volcano (Hackett & Houghton, 1989), formed via back-arc volcanism behind an active subduction zone at the Australian and Pacific plate boundary (Stern et al., 2006).

The stratigraphic framework of Mt Ruapehu comprises four formations, on the basis of geochronology, geochemistry, and stratigraphic relationships, pinpointing distinct spatial-temporal stages of volcano evolution (Figure 1a): Te Herenga (200–150 ka), Wahianoa (166–80 ka), Mangawhero (50–15 ka), and Whakapapa (<15 ka) Formations (Conway et al., 2016; Gamble et al., 2003; Hackett & Houghton, 1989; Price et al., 2012; Townsend et al., 2017). The only major hiatus in activity is from 80 to 50 ka, which was a period of erosion and edifice instabilities (Townsend et al., 2017).

The whole-rock chemistry of Mt Ruapehu varies between basaltic andesite and dacite (Price et al., 2012). Rock textures at Mt Ruapehu are mainly porphyritic with phenocryst abundances averaging 35–55% (Price et al., 2012); however, some lava flows exhibit aphyric texture. The main phenocrysts in decreasing abundance are plagioclase (8–39 vol%), clinopyroxene (2–14 vol%), orthopyroxene (2–10 vol%), magnetite and titanomagnetite (1–6 vol%), as well as rare occurrences of olivine and amphiboles (Conway et al., 2018; Gamble et al., 1999; Graham & Hackett, 1987; Nakagawa et al., 1999; Price et al., 2012; see detailed summary in Table S1). The composition of the plagioclase and pyroxene phenocrysts shows differences within the
main lithologic units, highlighting a changing magmatic source and edifice evolution over time (Conway et al., 2018; Kilgour et al., 2013).

The current volcanic edifice is made of mostly lava flows and their auto-breccias, with minor exposed volcaniclastic deposits, such as lahar, debris avalanche and tephra fall deposits (Conway et al., 2016; Townsends et al., 2017). Such lava flows seldomly reach the extensive ring plain around the volcanoes which preserved an extensive record of debris flows, debris avalanches, and hyperconcentrated flows with interbedded local andesitic and distal rhyolitic tephras (Donoghue & Neall, 1996; Pardo et al., 2012). Mt Ruapehu has produced 8–10 debris avalanches in the last 340 ky. The last two debris avalanches, Murimotu (9.5 ka) and Mangaio (4.6 ka), affected the NW and E sides and reached ~15 and 25 km distance, respectively (Donoghue & Neall, 2001; Palmer & Neall, 1989).

A recent period of magmatic activity occurred between September and November 1995 and June and July 1996, producing mild Strombolian to violent phreatomagmatic eruptions (Nakagawa et al., 1999). The 1995–1996 and 2007 eruptions exposed the top parts of the hydrothermal system, providing otherwise inaccessible samples to characterize the physicochemical state of the host rock and hydrothermal under the currently active Crater Lake (Christenson, 2000; Christenson et al., 2010; Christenson & Wood, 1993).

A previous magnetotelluric survey data were used to model the electrical resistivity structure of the upper flanks of Mt Ruapehu and its surroundings, indicating hydrothermally altered rocks located under the Summit Plateau (Ingham et al., 2009; Jones et al., 2008). Two higher resistivity zones (20–60 Ω m) located under the northern part of the Summit Plateau at 200–500 and 1,000–1,500 m depths are interpreted to be due to changing alteration mineralogy from smectite-illite to chlorite-rich zones (Jones et al., 2008). This region was further imaged using aeromagnetic data inversion and interpreted to be smaller demagnetized zones, corresponding to hydrothermally altered rocks (Miller et al., 2020). Besides Crater Lake (pH = 0–3, temperature range = 10–45°C), there is no surface expression of an active hydrothermal system on Mt Ruapehu (Christenson, 2000).

3. Materials and Methods
3.1. Field Sampling and Lab Analytics

A total of 64 samples was collected during field campaigns (Figure 1a). The samples are from lava flows (interior core and brecciated exterior) and tephra deposits and range from fresh to extensively altered. Some of the samples represent subsurface lithologies (upper 200 m), brought to the surface by the 2007 eruption-induced lahar and the ballistics from the 1995 to 1996 eruption. Samples were analyzed using lab-based reflected light spectroscopy, optical microscopy, and scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS).

Lab-based reflectance spectroscopy was completed using a FieldSpec 4 Hi-Res spectroradiometer, equipped with a Hi-Brightness contact probe with a sampling footprint of 10 mm in diameter. The samples were air-dried at 40°C for 24 h before analysis to ensure samples were dry. The spectral readings were calibrated against a white Spectralon Diffuse Reflectance Standard. Spectra measurements were completed at two to seven “spots” on each specimen, which assured representative sampling of the variation of the alteration within each sample. Each of these “spots” included at least 100 spectral measurements. All spectral measurements were then averaged using View Spec Pro software and later exported into a spectral library. When an alteration rim/crust was present on a sample, the interior and outer rim were analyzed separately. The averaged spectral reflectance was used to recognize the typical mineral association within the samples using continuum removed spectral curves (Clark & Roush, 1984). The wavelength of the absorption features (i.e., reflectance lows) was matched manually with the United States Geological Survey (USGS) Spectral Library Version 7 (Kokaly et al., 2017), as well as automatically using a Spectral Feature Fitting approach implemented in ENVI (Clark et al., 1990). A list of key spectral absorption features and descriptions is summarized in Table S2.

A subset of the samples was prepared for thin section SEM and EDS for petrographic and geochemical analysis. These samples were cut, mounted onto glass slides, and then ground to 30 μm and polished for optical microscopy, while other samples were ground to about 100 μm and polished for SEM-EDS analysis. The latter batch was carbon-coated and imaged using ThermoFisher Scientific™ FEI Quanta 200 Environmental
Scanning Electron Microscope operated in back-scattered electron (BSE) mode under accelerating voltage of 20 kV, with a working distance of 10 mm, at the Massey University's Manawatu Imaging Centre. BSE equipped with an EDAX EDS system was used to identify element abundance to characterize rock alteration types and secondary mineralogy.

Magnetic susceptibility measurements were made on tephra and rock outcrop and hand specimens using a Terraplus KT-10 v2 magnetic susceptibility meter. The Terraplus was held in direct contact with the surface of each sample on a flat surface if possible, measured three times, and averaged to produce one value per sample.

3.2. Hyperspectral Imaging and Image Classification

Aerial surveys were completed using a Cessna 185 survey aircraft, with two integrated imaging systems onboard, between 10:25 and 12:45 NZST on 31 March 2018. The survey aircraft hosted a Specim AisaFENIX hyperspectral imaging system, alongside a Nikon D810 digital single-lens reflex camera. The hyperspectral sensor captures reflected light between 377 and 2,500 nm with a total of 448 spectral bands. The spatial resolution of the imagery is 1.5 m. The detailed instrumentation and data processing are provided in the supporting information and Figure S1.

The hyperspectral imagery can be used to map the surface spatial distribution of hydrothermally altered mineral packages (Carrino et al., 2018; Murphy et al., 2015; Rogge et al., 2014; Zabcic et al., 2014), using supervised image classification. This requires training and validation data to be identified. This study uses the hydrothermal alteration mineralogy and their sample location as well as field observations to develop training and validation populations, split at 50–50% for the supervised image classification. The total area was split into five rock alteration classes based on the alteration mineralogy (e.g., unconsolidated-unaltered, unaltered lava rocks, supergene argillic alteration, intermediate, and advanced argillic alteration types) and three general classes (e.g., water, ice/glacier, and shadow). The alteration types were based on the observed mineralogy in the collected samples. This study used random forest classification (Breiman, 2001), which is effective at reducing overfits due to highly colinear data (i.e., hyperspectral imagery), while also being time-efficient, and yielding accurate results (Belgiu & Drăguț, 2016; Kereszturi et al., 2018; Pal, 2005). Random forest algorithm constructs decision trees using a subset of the training data and variables (i.e., spectral bands). Each tree is expanded until either the maximum number of input data were used or they reached the minimum impurity value (i.e., 0), based on the calculated Gini impurity measure (Belgiu & Drăguț, 2016; Breiman, 2001). In this study, the total number of tree models was 500, and at each split of the inputs, the square root of input total variables (i.e., 21 bands) was used. The class values were assigned using majority voting procedure based on the individual tree’s prediction. The resultant classification image was assessed using independent validation population, through calculating the overall accuracy and an error matrix of user’s and producer’s accuracies (Liu et al., 2007).

3.3. Helicopter-Borne Aeromagnetic Survey

A helicopter-based aeromagnetic survey was carried out 2 weeks after the hyperspectral surveys in April 2018. We collected 800 km of magnetic data with a Geometrics G822A Ce-vapor magnetometer flown at 50 m above ground at 250-m spaced flight lines which we reduced to 125 m over the Pinnacles and Summit Plateau. Sampling the magnetic field at 10 Hz results in a magnetic field value every 2 m. We corrected for diurnal variations using a local base magnetometer outside the survey region and subtracted the International Geomagnetic Reference Field (IGRF) at each data point location using the IGRF 2005 model. The data were leveled using widely spaced tie lies to minimize crossover difference and were gridded for visualization at 20% of the line spacing using a minimum curvature algorithm (see Miller, Schaefer, et al., 2020, for full details).

To map the spatial distribution of magnetic and non-magnetic rocks within Mt Ruapehu volcano, a magnetic vector inversion algorithm was used, which is implemented in the SimPEG inversion framework package (Cockett et al., 2015; Fournier et al., 2020; Miller, Schaefer, et al., 2020). The inversion accounts for remanent magnetism, common in volcanic rocks, by solving for both the amplitude and direction of magnetization. The inversion returns a 3D model of apparent susceptibility that we interpret in terms of altered versus fresh rocks, where high apparent susceptibility typically reflects unaltered rocks and low apparent susceptibility increasingly altered rocks. The inversion model uses a mesh with minimum dimensions of...
50 × 50 × 25 or 25 × 25 × 10 m over the Pinnacle Ridge and Summit Plateau areas. The typical apparent susceptibility values recorded from the model range from 0 to 0.05 SI, which can be interpreted as a degree of hydrothermal alteration, from fully demagnetized/altered to magnetic/fresh rocks, respectively (Miller, Schaefer, et al., 2020).

4. Results and Interpretations

4.1. Alteration Mineralogy

Physical samples were grouped based on their alteration mineral phases: (1) non-altered rock/deposits with minor surface weathering, (2) supergene argillic alteration with weathering rim, (3) intermediate argillic alteration and superimposed surface weathering, and (4) advanced argillic alteration. This classification scheme is based on the presence and absence of alteration minerals that represent distinct physicochemical alteration domains (John et al., 2008, 2019; Rye et al., 1992; Zimbelman et al., 2005).

4.1.1. Non-Altered Lithologies With Minor Weathering

The non-altered lithologies frequently occur on blocky lava flows with auto-breciated horizons (Figures 2a and 2b) and are characterized by absorption at wavelengths of 420, 480, 500–560, 1,912, and 2,200 nm and occasionally ±660, ±950, and ±1,430 nm (rh1, rh2, rh4–9). In thin section, the studied samples show mostly fresh porphyritic and rarely aphyric and vitrophyric textures (Figures 2c and 2d). The samples have about 30–50 vol% phenocrysts of plagioclase, clinopyroxene, and orthopyroxene, various amounts of Ti-rich magnetite, and rarely olivine (Figures 2c and 2d). The phenocrysts are often euhedral to subhedral and occasionally show glomerophytic appearance. Some of the phenocrysts show chemical zonation, melt inclusions, and sharp crystal boundaries, indicating their unaltered and fresh origin. The groundmass is made of tabular plagioclase microlites and volcanic glass. Some samples have a thin (≤1 mm) yellow- to brown-colored altertion rim, in which the groundmass is often replaced by secondary minerals, including phyllosilicates. The phenocryst phase appears to be still fresh (Figures 2c and 2d), but Ti-magnetite crystals rarely show trellis-type lamellae structures, especially within weathering rims. This can potentially indicate either high-temperature exsolution and oxidation during cooling (Tan et al., 2016) or due to hydrothermal alteration and surface weathering (van Hinsberg et al., 2010). The measured magnetic susceptibilities of this group range from 0.002 to 0.03 SI (Miller, Schaefer, et al., 2020), reflecting a wide range of variability of the (Ti-) magnetite content on Mt Ruapehu (Price et al., 2012).

The position of the absorption in the VNIR and SWIR regions can be explained by oxidation of primary mineralogy (e.g., magnetite, pyroxene) and limited but detectable development of secondary clay minerals, mostly in the groundmass, with and without alteration rims (Figure 2e). Such absorption is due to the presence of hydrous phases (e.g., 1,430, 1,912, and 2,200–2,350 nm and state transition from Fe²⁺ to Fe³⁺ between 400 and 1,000 nm) (Hunt & Ashley, 1979). Typically, the alteration rims contain more secondary minerals, such as goethite, ±ferrhydrite, ±phyllosilicate, and hematite. This observation is consistent for tephra, breccia, and lava rocks (Table S3). Moreover, most of the samples show similar spectral reflectance for both the core and rim in the SWIR region (rh19—Tawhainui lava flow, Iwigau Member, Whakapapa Formation), indicating the overall fresh, young (≤50 ky), and unaltered state of the samples.

4.1.2. Supergene Argillic Alteration

These samples have additional spectral features to the unaltered lithologies, at around 650, 950, 1,270, 1,430, 1,770, 2,050, 2,260, and 2,480 nm (rh10–11 and rh21–23). These are consistent with Fe oxides (e.g., goethite, hematite), with occasional jarosite and phyllosilicate phases, and are often limited to the alteration rim of the samples (Figure 3a). The alteration rims are often thicker than in the non-altered samples (>2 mm). The core is often composed of fresh phenocrysts and micro-phenocryst populations characterized by sharp boundaries and subhedral to euhedral crystals, lacking any pervasive alteration in the core of the samples (Figures 3c and 3d). This freshness of phenocrysts and micro-phenocrysts is also accompanied by magnetic susceptibilities, ranging from 0.005 to 0.02 SI (Miller, Schaefer, et al., 2020).

The spectroscopic data indicate the presence of both goethite and hematite on Mt Ruapehu, with a dominance of goethite. The formation of such alteration minerals is strongly pH dependent. Acidic (pH = 2–5) and alkaline conditions (pH = 10–14) favor the formation of goethite, while neutral pH promotes the formation of hematite (Schwertmann & Murad, 1983). However, both minerals can occur on the same hand specimens, indicating a highly heterogeneous occurrence of those minerals on a centimeter scale.
Figure 2. (a, b) Field photos of the fresh non-altered outcrop and (c, d) thin section photographs of a fresh lava sample under cross-polarized light in (c) and plane-polarized light in (d). cpx, clinopyroxene; m, magnetite; o, olivine; opx, orthopyroxene; plg, plagioclase. (e) Spectral reflectance profiles of the inner core and rim of rh2 sample (f). The main elements and element bonds are indicated as the cause of the light absorption. The reflectance values have been normalized using continuum removal (Clark & Roush, 1984).
Jarosite is common in the alteration rims, suggesting a supergene origin as a weathering product of Fe-bearing rocks. It often forms from oxidation products under acidic conditions and frequently forms in concert with ferric oxyhydroxides (Bishop & Murad, 2005). The jarosite phase (absorption feature at 2,265 nm; Figure 3e) is observed more often within the Te Herenga Formation (rh21–23) than in the Wahianoa Formations (rh10–11). This is consistent with the geochemistry of the original rocks (increased K and Fe content in the Te Herenga Formation; Table S1). The mineral assemblages are consistent with a paragenesis of a supergene argillic alteration and oxidation under atmospheric conditions, forming diverse alteration rims, depending on the primary rock geochemistry and the exposure time to alteration processes.

Figure 3. (a, b) Field and sample photos of the supergene argillic alteration showing various surface colorations and oxidations at outcrop scale. (c, d) Thin section photographs showing fresh phenocryst population with sharp contact (red arrow) viewed under cross-polarized light in (c) and plane-polarized light in (d). cpx, clinopyroxene; m, magnetite; opx, orthopyroxene; plg, plagioclase. (e) Spectral reflectance profiles of representative samples showing supergene argillic alteration minerals.
This process can be driven by metasomatism of K-bearing plagioclase phases by slightly acidic surface waters, causing surface weathering (Vasconcelos & Conroy, 2003).

4.1.3. Intermediate Argillic Alteration

This group is characterized by brownish to yellowish discoloration, with a partial to full replacement of the primary rock textures (Figures 4a–4c), as well as the development of pervasive alteration rims with distinct spectral reflectance (Figures 4d and 4e). These rocks have absorption around 380, 435, 490, 960, 1,420, 1,780, 1,915, 2,205, 2,290, 2,315, 2,390, and 2,480 nm with ±650, ±2,240, and ±1,100 nm (rh3, rh12, rh26–rh34, rh36–41). The presence of absorption features at 380, 430, and 480 nm with occasional ~650 and ~940 nm are due to Fe$^{3+}$ oxidation (Hunt & Ashley, 1979), indicating goethite as the main mineral phase with occasional jarosite, schwertmannite, and pyrrhotite (Figure 4e). These samples lack hematite, indicating formation under acidic conditions (Schwertmann & Murad, 1983). The SEM-EDS data further indicate that the groundmass of many alteration samples has disseminated subhedral pyrite with diameters between 5 and 30 μm (e.g., rh28, rh36, rh38, rh40; Figures 5a–5d). Larger 300- to 500-μm euhedral pyrite crystals are also present occasionally along grain boundaries and within cavities and fractures (e.g., rh38; Figure 5d). In addition to pyrite, Fe-rich, S-poor, and occasionally Mn-rich mineral phases have been identified, infilling cavity walls and fractures showing colloform, globular, and botryoidal morphologies (Figure 5a), which is

Figure 4. (a–c) Field photos of typical to intermediate argillic alteration on Mt Ruapehu. The samples are typically moderately to pervasively altered, showing various discoloration and clay mineral abundances. (d) Sample rh28 shows pervasive alteration preventing a clear distinction between crystal’s rim and core. (e) Spectral reflectance profiles of representative samples. The spectral reflectance curves show absorption feature SWIR related to atomic vibration between Al-OH, Fe-OH, and Mg-OH bonds, indicating the presence of phyllosilicates.
Figure 5. SEM (left column) and EDS (right column) results from the representative samples intermediate argillic alteration on Mt Ruapehu. The labeled EDS spots are color coded. (a) Sample rh28 shows typical phenocryst and micro-phenocrysts dissolution textures and extensive vug development with Fe-rich and S-poor infilling, comprising Fe oxides and Fe hydroxysulfates. This sample is representative for the base of the Pinnacle Ridge. (b) Sample rh34 shows vermiciform, fibrous, and tubular morphologies of smectite group mineral, occupying fracture and vugs. (c) Sample rh36 shows jarosite and goethite developed pseudomorphs after cubic pyrite. The groundmass is extensively replaced by silica (qtz). (d) Sample rh38 shows well-developed cubic pyrite crystals co-occur with kaolinite and smectite group clay minerals (e.g., #5 and #6 on EDS) occupying vugs developed in former phenocrysts. A smaller population of pyrite occupies the interior walls of former phenocrysts, shown by red arrows. cpx, clinopyroxene; fr, fracture; goe, goethite; js, jarosite; kao, kaolinite; m, titanomagnetite; opx, orthopyroxene; plg, plagioclase; py, pyrite; qtz, quartz; sm, smectites; su, Fe sulfates; v, void/vug.
consistent with Fe oxides (goethite) and Fe sulfates (schwertmannite). Jarosite occasionally appears as a pseudomorph after pyrite (e.g., rh36; Figure 5c). The paragenesis of this phase is interpreted to be after supergene oxidation of the sulfide-rich host rock under strongly acidic conditions (Nordstrom, 1982). The SEM-EDS results show a higher vol% of pyrite in the Wahianoa than Te Herenga Formation. This can indicate time differences (10–100 ky) since those deposits are exposed to atmospheric conditions.

Based on SEM-EDS data, both primary plagioclase and pyroxene phases alter to amorphous Si-rich phases, consistent with various polymorphs of quartz. The alteration leaves abundant rim and core dissolution structures with well-developed microfractures, occasionally colloform and pseudomorph crystal habits within cavities (Figure 5a). These are consistent with acid-induced mineral dissolution structures (Farquharson et al., 2019). Ti-magnetite phenocrysts and micro-phenocryst show commonly trellis-type lamellae textures, indicating leaching of the Fe and enrichment of Ti oxides and silicates (rutile and titanite), which is in association with pyrite formation. This alteration process is responsible for the decrease of magnetic susceptibility of this group, which is between 0 and 0.01 SI (Miller, Schaefer, et al., 2020).

The absorption positions at 1,420–1,430, 1,780, 2,205, 2,290, 2,315, and 2,390 nm are consistent with the abundance of Na-Mg-Ca-Fe-rich phyllosilicates, including both kaolin and smectite group minerals. The distinction within phyllosilicates is challenging; however, reflectance spectroscopy in the VNIR and SWIR can detect vibrational and overtone-derived absorption features with hydrous minerals (Hunt & Ashley, 1979). This study used the shape, asymmetry, and position of the absorption features to discriminate phyllosilicates and sulfates mostly in the SWIR (Table S2). Typically, samples with 1,415 and 2,205 nm (doublet) feature with inclination/asymmetry toward short wavelength were interpreted as kaolin group (e.g., kaolinite and halloysite). Absorption at 1,415 and 2,205 nm and typically at 2,290–2,310 nm with inclination/asymmetry toward the long wavelength indicated the presence of the smectite group. The smectite group minerals were further discriminated by the position of their absorption feature at the SWIR region: montmorillonite, nontronite, and vermiculite.

The presence of phyllosilicates is often as fracture infilling minerals, showing thin crystallites with a vermiciform, fibrous, and tubular morphologies with hollow interiors, with Mg and Fe enrichment (Figure 5b). These textural and morphological features also indicate smectite group minerals (Beauchamps et al., 2019; Ece et al., 1999; Ta et al., 2017), indicating the dominance of montmorillonite and nontronite. Some samples (rh26) contain zeolite group minerals with acicular and radial crystal habits, occurring in fractures and cavity infilling.

Occasionally, euhedral to subhedral, hexagonal to prismatic, and disseminated Cl-rich apatite crystals with diameters ranging from 30 to 50 μm are embedded in phyllosilicate dominated fracture infills. Apatite is a minor but ubiquitous mineral of plutonic and volcanic systems (Piccoli & Candela, 2002), and it is also present on Mt Ruapehu (Price et al., 2012). Constraining the paragenesis of this phase is problematic using spectroscopy, optical microscopy, and SEM-EDS analysis, and it requires cathodoluminescence (Bouzari et al., 2016). The apatite found in rh34 contains a minor amount of S and Si, which can be incorporated into the apatite’s crystal structure (Streck & Dilles, 1998), potentially indicating its magmatic origin.

Aluminum-phosphate-sulfate (APS) minerals occur in cavities as well-developed acicular crystals and are only observed in samples from the Wahianoa Formation. The SEM-EDS spectra is Ca-rich with minor peaks of Al and S, which might correspond to woodhouseite (Dill, 2001; Stoffregen & Alpers, 1987). These APS minerals occasionally complement acid sulfate alteration in high-sulfidation epithermal systems which are rich in Ca, P, and Al, dissolved from primary apatite and plagioclase phases (Imura et al., 2019; Stoffregen & Alpers, 1987).

The mineral associations and their spectral, chemical, and textural characteristics are all consistent with intermediate argillic alteration, formed in a highly acidic environment by hydrothermal fluids with temperatures between 150°C and 250°C (John et al., 2019; Simmons et al., 2005). This resulted in abundant pyrite as an oxidation product of the ascending H₂S-rich fluids below and around the paleowater table within the proto-Ruapehu edifice, within the Te Herenga and Wahianoa Formations. The pyrite-bearing rocks were then subject to supergene alteration after exposure to the atmospheric condition following flank collapses (Palmer & Neall, 1989; Tost et al., 2015) and erosion by glaciation and fluvial activity. This led to the formation of smectite group minerals, such as montmorillonite and nontronite, and Fe sulfates, potentially
schwertmannite, both filling in fractures and vugs. Smectite group minerals often form after the initial oxidation of pyrite, producing acid water, followed by hydrolysis of feldspar and acid water buffering by the host rock and colloidal deposition in open cavities and fractures at low temperature ($\leq 40^\circ$C) (Fernández-Caliani et al., 2004). This paragenesis often produces minor barite phase (Fernández-Caliani et al., 2004), which has been identified as a minor phase in XRD (Mordensky et al., 2019).

### 4.1.4. Advanced Argillic Alteration With Minor Silicification

Advanced argillic alteration occurs in vertical cliffs, and as reworked volcanoclastics deposits along the upper Whangaehu Valley, around the present-day Crater Lake area, and sampled as ballistic blocks from past eruptions (Figures 6a–6c). These samples are often characterized by white, gray to pale yellow colors with abundant native sulfur, gypsum, amorphous silica precipitation and pyrite crystals with diameters up to 2 mm (Figures 6a–6d). This group shows typical VNIR-SWIR absorption features around 380, 430, 480, 940, 1,412, 1,920, 2,170, 2,205, and 2,450 nm with $\pm 390$, $\pm 1,430$, $\pm 1,475$, $\pm 1,490$, $\pm 1,783$, $\pm 2,240$, $\pm 2,260$, $\pm 2,320$, and $\pm 2,400$ nm (Figure 6e). The spectral absorption position is consistent with goethite, phyllosilicates with the dominance of kaolin group minerals over the smectite group, native sulfur, sulfates, and sulfides. The SEM imagery shows completely dissolved phenocrysts and micro-phenocrysts of all primary
minerals (Figure 7a). The groundmass is often completely replaced by amorphous quartz with localized silicification (Figures 6a and 7). Occasionally, samples show intense local silicification with complete to partial replacement of groundmass and phenocrysts, accompanied by minor sulfur and barite precipitation.

Figure 7. SEM (left column) and EDS (right column) results from the representative samples advanced argillic alteration on Mt Ruapehu. The labeled EDS spots are color coded. (a) Sample rh35 shows tabular crystals of alunite, occurring together with kaolinite, pyrite, and quartz. The groundmass and phenocryst are completely replaced by the alteration mineralogy; however, scattered Ti-rich phases are residues after the primary Ti-rich magnetite population (ti). (b) Sample rh44 shows extensive veinlets of precipitated native sulfur. (c) Sample rh45 shows anhydrite filled fracture surrounded disseminated pyrite, alunite, and quartz. al, alunite; kao, kaolinite; py, pyrite; qtz, quartz; s, sulfur; ti, Ti-rich phase; v, void/vug.
The second largest unit mapped is the unaltered lava rocks (22.8 km²). Supergene, intermediate, and surface alteration occurs between the supergene argillic and the intermediate argillic alteration types (Table 1). However, the groundmass occasionally has stockwork textures and colloform banding with vein and veinlets filled by native sulfur (rh44; Figure 7b) and anhydrite (rh45; Figure 7c). Anhydrite can be formed by progressive removal of acid anion species, such as SO₄ from the hydrothermal fluids, or by the exchange of aqueous H⁺ with cations in the host rock (Smith et al., 2017; Zimbelman et al., 2005). This paragenesis can also result in precipitation of kaolinite (Hynek et al., 2013). Samples exposed on the surface for an extended period were subject to depletion of their sulfur content (rh12) and hydration processes, forming gypsum (rh48).

Besides anhydrite and gypsum, this group has alunite. Alunite exhibits spectral absorption features (Figure 6e) due to the vibrations of hydroxyl (-OH) and metal-oxygen bonds (Al-OH) and lattice vibrations (Bishop & Murad, 2005). The alunite occurs on Mt Ruapehu as tabular crystals and as a constituent of the groundmass (Figures 7a and 7c). Both reflectance and SEM-EDS data indicate that alunite on Mt Ruapehu is not a pure endmember, but they show both K and Na enrichments. The origin of alunite is due to the oxidation of acidic H₂S-rich fluids between the groundwater table and the surface (Zimbelman et al., 2005), or as supergene alteration of sulfides (Bladh, 1982). Currently, there is no surface hydrothermal manifestation (e.g., fumaroles, hot springs) besides the vent-hosted hydrothermal system beneath Crater Lake. The current Crater Lake and its hydrothermal system precipitate Na-alunite as oxidation of ascending H₂S hydrothermal fluids (Christenson & Wood, 1993). The formation of alunite within the Wahianoa Formation is interpreted to be formed under hypogene conditions due to its current stratigraphic position (e.g., exposed only at the lower parts of the Whangaehu Valley). However, further isotope and radiometric dating are needed to confirm its relationship with the currently active hydrothermal system under the Crater Lake area.

The mineral associations are consistent with advanced argillic alteration (e.g., Sillitoe & Hedenquist, 2003) formed from a low pH of 1–4, hot hydrothermal fluids (120–300°C), circulating within a magmatic-hydrothermal system (Boyce et al., 2007; John et al., 2008; John et al., 2019; Simmons et al., 2005; Swayze et al., 2014). However, the hydrothermal alteration can change on a small scale between advanced argillic and intermediate argillic alteration styles.

### 4.2. Surface Alteration Mapping Using Hyperspectral Imaging

The airborne hyperspectral image was used to create a hydrothermal alteration map of Mt Ruapehu through supervised image classification using a random forest algorithm (Figure 8). The training process for the image classification was guided by the hydrothermal alteration mineralogy from SEM-EDS and spectroscopy analysis. The image classification accuracy using an independent validation population is 92.6%. Full retrieval of alteration classification on the surface is affected by the heavy cover of tephra, snow, and ice on the surface of Mt Ruapehu (35.7% of the total area; Table 1 and supporting information) and the presence of shadows. The second largest unit mapped is the unaltered lava rocks (22.8 km²). Supergene, intermediate, and advanced argillic alteration have much smaller spatial extent on the surface, composing 4.8, 2.4, and 0.2 km² of the total area, respectively (Table 2). Accounting for the extensive surface cover, these hydrothermal alteration zones are expected to be minimum figures. The spectral average of the input training data shows distinct differences, including spectral features at 405, 493, 670, and 995 (goethite, hematite); 1,160 (smectites); 1,430–1,495 (kaolinite, alunite, jarosite); 1,763 (alunite); 2,174 (alunite); 2,200–2,210 (Al-rich phyllosilicates); 2,265 (jarosite); and 2,300–2,390 nm (Fe- and Mg-rich phyllosilicates) (Figure 9). These indicate that those minerals are critical to spectrally separate the mapped hydrothermal alteration types using airborne hyperspectral imagery.

The error matrix shows numerous misclassifications between unconsolidated tephra and unaltered lava rocks (Table 1). This can be due to the similar chemical composition, resulting in similar reflectance profiles. Therefore, the spectral discrimination is most likely due to overall intensity of the reflected light, which, in turn, is a function of the grain size and illumination geometry (Clark & Roush, 1984). Another misclassification occurs between the supergene argillic and the intermediate argillic alteration types (Table 1). However,
Figure 8. Hydrothermal alteration map of Mt Ruapehu based on the airborne hyperspectral imagery (a). The black arrows show the location of the reworked deposits of the advanced argillic alteration (rh44, rh45) along the upper Whangaehu Valley. Classes 1–4 are not shown for clarity. The reader is referred to the supporting information for the full image classification figure.
this misclassification occurred less frequently due to the presence of an absorption feature at 671 nm (e.g., goethite, ferrihydrite, and hematite).

The most spectrally distinct class is the advanced argillic, due to its unique and pronounced absorption located at 2,174 (alunite) and 2,205 nm (kaolinite). The mapped occurrences correspond to three distinct elevation regions (Figure 10): (1) the lower occurrences correspond to the reworked deposits, along with the Whangaehu Valley (black arrows in Figure 8). The other two populations can indicate a spatial and temporal difference between the formation of advanced argillic suites (e.g., Wahianoa Formation vs. the current Crater Lake hydrothermal system).

### 4.3. Subsurface Mapping Using Aeromagnetic Data

The 3D depth of hydrothermal alteration can be mapped using aeromagnetic data and subsequent inversion models (Finn et al., 2018, 2001; Miller, Schaefer, et al., 2020), if the lack of the magnetic susceptibility is due to hydrothermal alteration which dissolves (Ti-) magnetite crystals. Based on the SEM imaging, there is a systematic dissolution of (Ti-) magnetite with increasingly pervasive hydrothermal alteration (Figures 11a–11c). Therefore, the magnetic susceptibility measurements and the inversion model of Mt Ruapehu (Miller, Schaefer, et al., 2020) indicate the hydrothermal alteration, which can be used to link surface alteration patterns from the hyperspectral image classification (Figure 11d). However, identifying low magnetic susceptibility caused by hydrothermal alteration is complicated by the variable amounts of magnetite content and its Ti impurity in the host rock (Figure 11d), meaning that some fresh, low magnetite content andesites can have similar magnetic susceptibility to supergene alteration. Intermediate and advanced argillic alteration deposits tend to have, however, generally lower magnetic susceptibility (< 0.01 SI; Figure 11d).

### Table 1

| Image class | Validation class | Water | Ice | Shade | Tephra | Unaltered lava | Supergene argillic | Intermediate argillic | Advanced argillic | Total |
|-------------|-----------------|-------|-----|-------|--------|----------------|-------------------|---------------------|-----------------|-------|
| Water       | 3,381           | 132   | 44  | 0     | 0      | 0              | 0                 | 0                   | 0               | 3,557 |
| Ice         | 0               | 1,952 | 0   | 0     | 0      | 0              | 0                 | 0                   | 0               | 1,952 |
| Shade       | 0               | 0     | 5,820| 4     | 0      | 0              | 0                 | 0                   | 0               | 5,824 |
| Tephra      | 2               | 0     | 5,999| 699   | 9      | 3              | 18                | 16,330              |                 |       |
| Unaltered lava | 5        | 0     | 1,094| 26    | 1,203  | 77             | 69                | 0                   | 3,064           |
| Supergene argillic | 0      | 0     | 0    | 47    | 26     | 77             | 42                | 0                   | 1,318           |
| Intermediate argillic | 0    | 0     | 0    | 68    | 148    | 727            | 2                 | 945                |
| Advanced argillic | 0  | 0     | 0    | 0     | 0      | 3              | 0                 | 595                | 598             |
| Total       | 3,388           | 2,084 | 5,864| 16,744| 2,612  | 1,437          | 844               | 615                 | 33,588          |

*Note. The values are pixel numbers. Bold values show the correctly classified pixels.*
The largest region of hydrothermally altered rocks is located within the Pinnacle Ridge on the southeastern flank and to a moderate extent beneath the entire Summit Plateau. The cross-cutting dykes exposed at the Te Herenga Formation show higher magnetic susceptibility compared to the lavas of the Wahianoa Formation, due to differences in original petrology and grain size of the intruded rocks. The low to moderate levels of magnetic susceptibility (Turoa side; Figure 12a) are due to volcaniclastic deposits, mixed with glacial...

Figure 9. Continuum-removed spectral reflectance curves for the alteration classes on Mt Ruapehu, showing spectrally distinct absorption features of each class and the inferred mineralogy (black arrows) due to their unique mineralogy (right column). The graph also indicates the location of the atmospheric gases, manifesting as noise in the hyperspectral data. The spectral curves are offset for clarity. al, alunite; goe, goethite; hem, hematite; js, jarosite; kao, kaolinite; sm – smectites.

The largest region of hydrothermally altered rocks is located within the Pinnacle Ridge on the southeastern flank and to a moderate extent beneath the entire Summit Plateau. The cross-cutting dykes exposed at the Te Herenga Formation show higher magnetic susceptibility compared to the lavas of the Wahianoa Formation, due to differences in original petrology and grain size of the intruded rocks. The low to moderate levels of magnetic susceptibility (Turoa side; Figure 12a) are due to volcaniclastic deposits, mixed with glacial...

Figure 10. Histogram of the elevation value within the advanced argillic alteration class, indicating three occurrences. The lowest values occur along the Whangaehu Valley, which has been interpreted to be reworked, while two in situ occurrences are located within the Wahianoa Formation.
sediments and thin intercalated lava flows (Conway et al., 2016; Townsend et al., 2017), with some that might also be hydrothermally altered (Miller, Schaefer, et al., 2020). The demagnetized zones beneath Summit Plateau are patchy (Figure 12b), in agreement with electrical resistivity highs observed in the magnetotelluric model, which suggest the dominance of chlorite (Jones et al., 2008). The geophysical model linked with alteration mineralogy and surface alteration distribution from the hyperspectral imaging indicates that the hydrothermal alteration interpreted in the aeromagnetic model mostly corresponds to intermediate argillic alteration. Intermediate argillic alteration is rich in smectite group minerals, which can explain the observed high electrical resistivity zone beneath the northern part of the Summit Plateau (“R1” anomaly in Jones et al., 2008). Moreover, this alteration type has a wide range of magnetic susceptibilities (0.001 to 0.01 SI) (Figures 11d and 12), contributing to the patch-work patterns in the aeromagnetic data (Miller, Schaefer, et al., 2020).

5. Discussion
5.1. Integration of Hyperspectral Imaging With Airborne Geophysics
Airborne hyperspectral remote sensing can identify hydrothermal alteration minerals, and through image classification, a hydrothermal alteration map can be created. The hydrothermal alteration map only

Figure 11. Titanomagnetite dissolution textures as a function of hydrothermal alteration types: (a) non-altered, (b) intermediate with well-developed trellis structures, and (c) advanced argillic alterations. (d) The graph shows the relationship between measured magnetic susceptibility values (SI) and spectral reflectance at 2,205 nm.
represents surface alteration, which can be heavily hampered by the surface cover (e.g., tephra, glacial till, alluvium, and colluvium accumulation). However, the distribution of the hydrothermal alteration (both in-site and reworked volcaniclastic deposits) can still be reconstructed with the aid of ancillary field data through microscopic petrographical and mineralogical information. Hyperspectral imaging provides a versatile framework for hydrothermal alteration mapping, which correlates well with the magnetic susceptibility model of Mt Ruapehu (Figure 12). Conversely, the inversion of aeromagnetic data can indicate spatial distribution of subsurface alteration at depth, but it provides no information on the style of hydrothermal alteration, and interpretation of moderate alteration can be misled by unaltered rocks with similar magnetic susceptibility. Furthermore, aeromagnetic data are also insensitive to rock water saturation that is a key determinant in slope stability (Finn et al., 2018; Miller, Christenson, et al., 2020). Thus, limitations in both hyperspectral remote sensing and geophysical data can be overcome by integrating both methods, allowing a comprehensive assessment of both surface and subsurface alteration patterns.
The paragenesis of hydrothermal alteration types and volumes of the altered rock masses provide a great conceptual model for volcanic hydrothermal systems, vastly improving our understanding of volcanic evolution and associated natural hazards. Specifically, Mt Ruapehu has hydrothermally altered lithologies exposed along ridge tops and on steep slopes due to tephra cover and erosion, which might seem minor. However, geophysical data, such as aeromagnetic, suggest that a much larger extent is altered. This is likely the case at similar long-lived volcanoes worldwide. This calls for the need to integrate remote sensing and geophysical data sets for developing new volcano assessment tools to monitor and map shallow hydrothermal alteration within composite volcanoes.

A limitation of the proposed combination of methods is the lack of data on water saturation, which can be an important driver for pore pressure fluctuation in volcanic aquifers (Finn et al., 2018). Therefore, a useful add-on can be for future studies to combine those survey techniques above with electrical and electromagnetic geophysical methods, such as direct-current resistivity, induced polarization, and airborne electromagnetics. These methods need to be included in current monitoring methods to improve our understanding of the trigger mechanism of slope failures and rock mechanical properties.

5.2. Mineral Overprinting and Preservation of Alteration Minerals

The weathering and hydrothermal alteration on Mt Ruapehu has produced diverse mineral suites, some of which can be formed through multiple parageneses including supergene modification through oxidation of sulfides, such as pyrite exposed to groundwater or surface water (Figure 13a). These processes cause changes to meta-stable hydrothermal alteration minerals, leading to overprinting, complicating the reconstruction of hydrothermal alteration history on long-lived composite volcanoes. For example, supergene oxidation can

Figure 13. A model for surface weathering and hydrothermal alteration on Mt Ruapehu volcano. (a) Hydrothermal alteration sequence of typical primary minerals (green), and their supergene argillic (blue), intermediate (pink), and advanced (red), their supergene overprinting mineral associations. (b) The distribution of hydrothermal alteration types and the main hydrothermal features on Mt Ruapehu along the A-A’ profile line in (c). SP glacier, Summit Plateau glacier.
form jarosite (in Fe-rich low-pH conditions), alunite (in moderate pH and Al-rich conditions), as well as hydroxysulfate and oxyhydroxide minerals (Bishop & Murad, 2005; Schwertmann & Murad, 1983; Zolotov & Shock, 2005). Mt Ruapehu has abundant Fe oxides, such as goethite, which can be formed from both oxidation processes of primary mineral phases rich in Fe (e.g., titanomagnetite, clinopyroxene, and orthopyroxenes) and oxidation and breakdown of hydrothermal pyrite (Brady et al., 1986; Noack et al., 1993). Such contrasting paragenesis cannot be distinguished by hyperspectral imaging alone. The abundance of goethite, and its confinement to higher flanks, can also be attributed to Ruapehu's extensive glacial history (Cole et al., 2020). The chemical weathering occurring beneath glaciers is primarily driven by microorganic activity, thriving on meltwater solution rich in oxidized pyrite, silica, and SO$_4^{2-}$ anions (Mitchell et al., 2013; Rutledge et al., 2018), which can form extensive goethite by interacting with magnetite content of the host rocks on the surface.

The integration of field sampling, hyperspectral, and aeromagnetic data have, however, allowed us to constrain the spatial distribution of inactive and currently active hydrothermal systems, allowing discrimination of mineral overprinting processes on Mt Ruapehu (Figure 13b). These correspond to the oldest Te Herenga Formation, outcropping at the Pinnacle Ridge, in which the intrusion-related hydrothermal system leads to acid sulfate alteration, causing primary mineralogy to be altered to pyrite, phyllosilicates, and quartz-dominated alteration minerals, superimposed with extensive smectite formation due to prolonged surface oxidation of pyrite (Figure 13b). This leads to distinct vertical and stratigraphic changes in a sulfide-to-clay ratio within the altered rocks. Areas <2,000 m a.s.l. show less extensive oxidation of pyrite (e.g., rh28) than the elevated, >2,100 m a.s.l parts of the Pinnacle Ridge (rh32–34). This can be explained by the delay in surface erosion and thus the exposure of the sulfides to atmospheric O$_2$, leading to enrichment of smectites.

The second oldest part of Mt Ruapehu is the Wahianoa Formation that hosts extensive areas of intermediate argillic alteration (Figure 13b). The alteration mineralogy and textures (e.g., sharp boundaries of the pyrite crystals) are better preserved than within the Te Herenga Formation, indicating much shorter exposure to atmospheric conditions. This observation is in line with the geological history of the upper Whangaehu Valley (Figure 1), which developed after the Mangaio Valley (Figure 1), which developed after the Mangaio collapse at 4.6 ka (Donoghue & Neall, 2001). Furthermore, the Wahianoa Formation also hosts advanced argillic alteration (e.g., alunite, pyrite, quartz, and phyllosilicates). This can originate from (1) surface oxidation of pyrite, (2) a magmatic-hydrothermal system that existed during the Wahianoa Formation time, or (3) a steam-heated overprinting alteration due to the proximity of the currently active Crater Lake hydrothermal systems by condensation of magmatic vapor into the later outflow of groundwater (Figure 13b). In (2) and (3), the alunite formed directly due to the ascent-driven oxidation of H$_2$S-rich fluids and wall-rock interactions. Alunite, however, occurs with anhydrite on Mt Ruapehu, which is more consistent with the paragenesis of (2). The distribution of alunite-bearing rocks can therefore indicate the position of the paleowater table within the Wahianoa eruptive center. Based on the two modes of advanced argillic alteration packages (Figure 10), it is likely indicating a complex spatiotemporal hydrothermal history. The lowest levels of in situ alunite within the Wahianoa Formation is at 2,250 m a.s.l. This elevation is just slightly higher than the maximum elevation of the Pinnacle Ridge (2,237 m a.s.l.), which lack of any alunite, potentially indicating the role of erosion on the preservation of alunite-bearing rocks.

5.3. A Model for Hydrothermal Alteration

Aeromagnetic and hyperspectral data show that Mt Ruapehu currently has an active but spatially confined vent-hosted hydrothermal system. This is in sharp contrast with the neighboring Tongariro volcanic complex, which has abundant hydrothermal features, including fumaroles and hot pools (Miller et al., 2018; Moore & Brock, 1981). While there is a limited surface hydrothermal alteration on Mt Ruapehu (i.e., intermediate and advanced argillic styles), covering 2.6 km$^2$ or only 5% of the total area (Figure 8), the location of this alteration is scattered throughout the mapped areas. This indicates a complex spatial-temporal evolution of hydrothermal activity at Mt Ruapehu that reflects discrete development stages over the last 200 ky (Figure 13).

At Mt Ruapehu, the source of the magmatic heat and gases are located at depths between 2 and 9 km as a network of stalling and crystallizing dykes, forming a melt-rich crystal mush inferred from volatile content and major element chemistry of groundmass glass and phenocryst-hosted melt inclusions (Kilgour...
This zone has also been imaged as a resistivity anomaly in magnetotelluric (Ingham et al., 2009) and seismic tomography surveys (Rowlands et al., 2005). This network of magma releases magmatic gases (H₂O, CO₂, and SO₂; Figure 13b), which after disproportionation can form acidic hydrothermal fluids dominated by H₂S, and precipitate native sulfur (Christenson et al., 2010; Mavrogenes & Blundy, 2017). This type of hydrothermal fluid promotes acid sulfate wall-rock alteration within the volcanic edifice above the magmatic heat source (Rye et al., 1992; Zimbelman et al., 2005). The low-pH hydrothermal fluids then induce wall-rock alteration at depth underneath the currently active Crater Lake. A similar ancient hydrothermal system has been imaged by magnetotelluric surveys beneath the northern Summit Plateau as a vertically elongated high-resistivity zone, which can correspond to a chlorite-rich altered zone (Jones et al., 2008). Chlorite is a typical indicator mineral of propylitic alteration (Neal et al., 2018). A broader region around this zone also appears to be demagnetized (Figure 13b; Miller, Schaefer, et al., 2020), which can correspond to the development of an enlarged alteration halo (Figure 13b).

Propylitic alteration often grades vertically into intermediate argillic alteration (e.g., John et al., 2019), which outcrops only sporadically around the Summit Plateau (Figure 8). This type of alteration occurs as the ascending H₂S-rich hydrothermal fluids react with the andesitic host rock's ferrous minerals (e.g., titanomagnetite) to form sulfides, such as pyrite, under reducing conditions (Figure 13a), as observed similarly at Mt Rainer, United States (John et al., 2008). On Mt Ruapehu, well-developed, cubic pyrite crystals are typical, indicating hydrothermal fluid supersaturation conditions and higher formation temperatures of ~250°C (e.g., Murowchick & Barnes, 1987). This zone has also been mapped as a higher-resistivity zone on magnetotelluric data (e.g., R1 in Figure 13b; Jones et al., 2008), indicating the dominance of intermediate argillic alteration beneath the entire Summit Plateau (Figure 13b). This area corresponds to the relict hydrothermal system of the Paretetaitonga and Tureiti cones, active between 20 and 12 ka (Townsend et al., 2017). Besides the precipitation of pyrite and enrichment of Ti, the wall-rock alteration on Mt Ruapehu also leads to K and partial Na and Ca depletions and Si, Al, Fe, Mg, and O enrichments, along with the formation of kaolin and smectite group minerals (Figure 13a).

At locations of intense hydrothermal fluid circulation, the intermediate argillic alteration transitions into advanced argillic alteration, characterized by the abundance of sulfate minerals (e.g., alunite) and localized zones of silicaification (e.g., vuggy texture). Sulfates (e.g., alunite, anhydrite, and barite) often form around or above the water table within a hydrothermal system due to oxidation of the ascending H₂S-rich fluids (Rye, 2005; Zimbelman et al., 2005). These are limited to areas directly beneath the Crater Lake and within the Wahianoa Formation (Figure 13b). The origin of sulfate precipitation within the Wahianoa Formation can be either (1) associated with the magmatic-hydrothermal system developed during the Wahianoa Formation, or (2) formed as a steam-heated alteration on the margin of the currently active Crater Lake hydrothermal systems due to lateral flow of groundwater (Figure 13b). The origin can be further investigated using stable isotope geochemistry, K-Ar and ⁴⁰Ar/³⁹Ar radiometric dating on the K-phase within the alunite.

5.4. Volcanic Hazard Implications

Volcanoes can progressively weaken through hydrothermal alteration and may collapse without warning. Mt Ruapehu and many composite volcanoes globally are often located near critical infrastructure and population, requiring a detailed assessment of flank collapse hazards. The existence of a single vent-hosted hydrothermal system at Mt Ruapehu suggests that current (ongoing) hydrothermal alteration may be limited to the active summit crater and conduit. However, lab and airborne hyperspectral and aeromagnetic data suggest that an abundance of alteration exists in the upper parts of the south and southeast flanks, either due to lateral fluid migration and/or older/inactive hydrothermal systems. The existing geophysical data indicate widespread hydrothermal altered rocks underneath the Summit Plateau, which is likely to be due to intermediate argillic alteration based on mineralogical and hyperspectral data (Figure 13b). The reconstructed mineral suites and hydrothermal alteration map can be combined with ongoing rock mechanical studies at Mt Ruapehu to provide an improved understanding of the geomechanical properties and rock stability. This, combined with volume estimates of altered bodies from aeromagnetic data (Miller, Schaefer, et al., 2020), is vital information for both defining the probability of failures initiating from these areas and implementing new numerical simulations of mass flows from composite volcanoes. These are topics of ongoing research to characterize geotechnical and volcanic hazards at Mt Ruapehu.
Besides flank collapse hazards, the dominance of intermediate argillic alteration can also alter overall strength, density, and elasticity of the host rocks (Mordensky, Heap, et al., 2019; Siratovich et al., 2016; Watters et al., 1995; Wyering et al., 2014). Experimental observations have also shown that an increase in alteration increases the propensity for pore collapse or ductile failure behavior (Mordensky, Heap, et al., 2019; Siratovich et al., 2016), which decreases porosity and permeability as the material is deformed, and pores are compacted (e.g., Farquharson et al., 2017). This, in turn, has implications for pore fluid pressure, magma degassing, and eruption characteristics (Cassidy et al., 2018; Heap et al., 2019; Okumura & Sasaki, 2014). For example, a reduction in permeability from clay precipitation into pores and fractures can prevent the migration of hydrothermal fluids or magma degassing at Ruapehu, leading to increased pore pressures that can decrease material strength (leading to collapse events) and increase the likelihood of phreatic eruptions (e.g., Day, 1996). The presence of clays can also reduce the effective pressure required for ductile behavior, resulting in an anomalously shallow ductile zone that may prevent brittle fracturing and thus volcano-tectonic seismicity prior to some volcanic eruptions (Mordensky, Heap, et al., 2019).

6. Summary and Conclusions

The present study integrates alteration mineralogy with hyperspectral imaging and aeromagnetic data inversion to provide a conceptual model for hydrothermal alteration. These geophysical and geochemical techniques can also be essential to map the 3D distribution of altered rock masses on composite volcanoes. However, the methods used in this study separately would not be able to fully describe the hydrothermal alteration. A combined approach is therefore promoted here to better understand such complex geosystems. This is particularly important for composite volcanoes with long-lived and nested eruptive centres, which can leave behind relict hydrothermal systems, potentially invisible on the surface.

Hyperspectral imaging is extremely effective at delineating surface hydrothermal alteration through image classification techniques, allowing quantitative recognition of hydrothermal alteration minerals. Furthermore, airborne imaging system allows very high-resolution imagery to be acquired, benefitting a detailed spatial mapping of hydrothermal alteration styles due to their unique combination of mineralogy. However, this technology currently is not capable of assessing deep-seated hydrothermal alteration and was limited by unconsolidated tephra, snow and ice cover, and shadow.

Aeromagnetic inversion models can complement airborne hyperspectral imaging to quantify subsurface hydrothermal alteration, by mapping the volume of demagnetized rocks. Hence, the combination of the airborne remote sensing and geophysical approaches allows the creation of a detailed, three-dimensional conceptual model for supergene weathering and hydrothermal alteration processes over the last 200 ky at the Mt Ruapehu volcano.

The detailed surface and subsurface imaging data provide versatile and high-resolution baseline information for future studies, which is critical to assess future volcanic activity and spatial/temporal changes on frequently active volcanoes. The methods used herein can be extended to other composite volcanoes worldwide. Results from these studies, in combination with mechanical information on rock strength, can be applied to identify the volume and configuration of structurally weak material. Better identification and delineation of flank instability hazards, obtained through detailed mapping of hydrothermal alteration, can be used to improve hazard assessment and mitigation efforts around active volcanoes.

Data Availability Statement

The airborne hyperspectral image is publicly available (10.5281/zenodo.3905352), as well as the aeromagnetic data (https://figshare.com/articles/Data_and_python_script/11289149).

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