

Key Points:

- Visible to near infrared (VNIR) plagioclase feldspar absorptions are detected in felsic rocks at plagioclase abundances <40 vol.%, despite association with hydrous mafic minerals
- Mineral grain size, iron content, and alteration history are primary controls on the detectability of plagioclase in VNIR spectra
- Intrusive felsic rocks exhibit a 1.25 μm plagioclase absorption that is likely detectable on Mars

Supporting Information:

Supporting Information may be found in the online version of this article.

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Visible to Near-Infrared Properties of Felsic Rocks: Plagioclase Detection Limits and Applications to Mars Orbital Spectra

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Abstract Widespread plagioclase detections on Mars using orbital visible to near infrared (VNIR) reflectance spectra have led to multiple interpretations of “feldspathic” terrain, ranging from ancient crustal material and evolved plutons to volcanic lava flows. A systematic, laboratory-based study of plagioclase detectability in whole igneous rocks is needed to contextualize these detections. We analyzed 42 feldspar-bearing igneous rocks (~50–77 wt.% SiO₂; ~25–60 vol.% plagioclase) using VNIR and mid-infrared (MIR) laboratory spectra, bulk chemistry/mineralogy, microscopic analyses of rock texture, and plagioclase chemistry to assess the characteristics influencing plagioclase signatures in whole-rock spectra. We find that 1.25 μm absorption bands are common in intrusive samples, and that plagioclase can be spectrally detected at abundances <40 vol.%, even in the presence of ~20 vol.% mafic hydrous minerals. We find that large (mm-scale) grain size is a driver of plagioclase detection, and that oxides are highly effective at subduing absorption bands. Plagioclase with a wide range of compositions (An_{25–47,90}) can produce a 1.25 μm absorption, unless iron-depleted (<0.13 wt.% FeO). Alteration can obscure the 1.25 μm absorption, causing rocks with similar plagioclase abundances and chemistries to exhibit different bulk VNIR spectra. Unambiguous detection of feldspathic rocks on Mars is only likely for: (a) plagioclase-rich crust (e.g., anorthosites or other plagioclase cumulates), (b) intrusive felsic rocks with limited alteration and plagioclase with iron >0.13 wt.%, and (c) plagioclase-phyric effusive rocks with little or no mafic phenocrysts. MIR spectra can distinguish felsic (granite, granodiorite, monzonite) and mafic (anorthosite, basalts) rocks with similar 1.25 μm absorptions.

Plain Language Summary Plagioclase feldspar, a fundamental rock-forming mineral, has been widely detected across the surface of Mars via visible- to near-infrared orbital spectra. These detections have yielded multiple hypotheses for the types of rocks responsible, ranging from excavated crust of ancient Mars to lava flows. To improve context for these detections, we analyzed laboratory data from 42 plagioclase-bearing rocks that cover a wide compositional range, with a focus on higher-silica “felsic” rocks. We find that 1.25 μm absorptions characteristic of plagioclase are common among slowly cooled igneous rocks (intrusive rocks) at plagioclase abundances <40 vol.%, lower than the expected minimum quantity for detection, even when mafic hydrous minerals are also present. Mineral grain size, iron content, and alteration are primary controls on the detectability of plagioclase, and oxide minerals are effective at subduing spectral bands of multiple mineral types. When considering orbital observations of plagioclase on Mars, detection clearly attributable to plagioclase is only likely for: (a) plagioclase-rich crust, (b) intrusive felsic rocks with limited alteration and plagioclase without depleted iron, and (c) volcanic flows with large plagioclase crystals and little to no mafic crystals. In addition, mid-infrared spectra can distinguish felsic rocks and lower-silica rocks with similar 1.25 μm absorptions.

1. Introduction

Silicic (>63 wt.% SiO₂) and plagioclase-rich rocks are known or hypothesized to be present on the Earth, Moon, Mars, Venus, and Vesta. However, the spectral character of felsic rocks in the visible to near infrared (VNIR; 0.5–2.7 μm) wavelength range is poorly understood. The VNIR spectral range is sensitive to iron in mafic minerals, which most felsic rocks do not contain in high abundance. As a result, felsic rocks have generally not been considered when interpreting the surface geology of rocky planets with orbital VNIR spectra. However, plagioclase feldspar is common in felsic rocks and could be detectable using VNIR spectra.

Plagioclase is an important component across the compositional spectrum of igneous rocks, as it is commonly a major mineral phase in mafic (~45–52 wt.% SiO₂) through felsic (>63 wt.% SiO₂) compositions. Fe²⁺-substitution in plagioclase can cause a broad VNIR absorption band at approximately 1.25-μm (Adams & McCord, 1971; Burns, 1970, 1993), but this band is relatively weak compared to mafic mineral absorptions, and can be easily obscured unless the material is plagioclase-dominated or the other components are predominantly spectrally neutral (Adams & Goullaud, 1978; Cheek & Pieters, 2014; Serventi et al., 2013). Currently, our understanding of VNIR plagioclase detection largely relies on pure mineral mixtures of fine grain size that are most applicable to regolith-dominated airless bodies like the Moon (Cheek & Pieters, 2014; Ohtake et al., 2009). These studies conclude that plagioclase must be in very high abundance (>85 vol.%, if mixed with mafic minerals) to be unambiguously detected in the VNIR range. However, these studies do not consider how grain size and rock texture in whole igneous rocks may affect plagioclase detectability, especially those with more felsic lithologies (e.g., coarse-grained intrusives like granodiorite, monzonite and granite). Because of this knowledge gap, we are not fully equipped to interpret the breadth of potential lithologies on Mars, a planet with extensive bedrock composed of diverse igneous lithologies rather than thick regolith (e.g., C. S. Edwards et al., 2009; Fergason et al., 2006; McSween et al., 2003; Putzig et al., 2005; Rogers et al., 2005; Sautter et al., 2015, 2016).

Over the past ~10 years, there have been a growing number of detections of plagioclase-like absorption in VNIR reflectance data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007), which are widespread across the martian surface (Carter & Poulet, 2013; Eggers et al., 2021; Flahaut et al., 2023; Payré et al., 2022; Phillips et al., 2022, 2025; Rogers & Nekvasil, 2015; Viviano-Beck et al., 2017; Wray et al., 2013). These detections are inferred to require rocks volumetrically dominated by feldspar (≥50 vol.% plagioclase + alkali feldspar), which we refer to as “feldspathic” (Frost & Frost, 2008). A number of hypotheses have been put forward to explain these detections, including anorthosites, intermediate and felsic rocks, and “plagioclase-phyric” basaltic rocks. Anorthosites are presumed to be dominated by plagioclase feldspar (>90 vol.% plagioclase), but that is not necessarily the case for felsic rocks which commonly contain 30–50 vol.% plagioclase. Intermediate rocks are defined as 52–63 wt.% SiO₂, and felsic rocks as those with 30–50 vol.% plagioclase and >63 wt.% SiO₂. “Plagioclase-phyric” refers to basalts with large plagioclase (Rogers & Nekvasil, 2015), which we specifically used to describe basalts with abundant >0.5 cm plagioclase phenocrysts. Each hypothesis for the lithology of these feldspathic outcrops implies a different petrogenesis with disparate implications for crustal evolution and magmatism on Mars. However, more information is needed about the range of compositions and mineral abundances that could produce these orbital VNIR plagioclase detections to constrain their formation processes.

In this study, our primary aim is to understand how the VNIR spectra of felsic rocks change based on factors like composition, crystallization history, and rock texture and grain size, with a particular focus on the quantity of plagioclase needed for detection (i.e., plagioclase detection limits). Basalts with coarse plagioclase phenocrysts (>0.75 mm, up to 1 cm) are also included to test the plagioclase-phyric basalt hypothesis. We used a suite of spectral and microscopic techniques to analyze igneous rocks with a wide range of silica and plagioclase content, crystallinity, and plagioclase chemistry to provide stronger constraints for orbital detections on Mars, and to determine what types of rocks are capable of exhibiting a 1.25 μm absorption consistent with plagioclase. Since it is already known that plagioclase-rich (>90 vol.%) rocks can exhibit strong plagioclase absorptions (Carli & Sgavetti, 2011), the range of silica and plagioclase content in our sample set fills a critical gap in interpreting spectra of rocks with moderate plagioclase abundance (30–50 vol.%). We describe spectral properties of the samples, along with strategies for using combined VNIR and mid-infrared (MIR; 5–25 μm) analyses that improve our ability to interpret orbital plagioclase detections on Mars.

Importantly, we find plagioclase may be clearly detected in phaneritic intrusive rocks at lower abundances (<50 vol.%) than is generally considered possible for detection in the VNIR range, and that mineral grain size, plagioclase iron content, and alteration history are likely the most important factors for detection. These results are complementary to recent studies by Barthez et al. (2023, 2026) that show plagioclase detection may be possible at lower abundances in whole-rock VNIR reflectance spectra. Our results imply a wide range of plagioclase-bearing lithologies, like granodiorites and plagioclase-phyric basalts, may be feasibly detectable from orbit on Mars.

2. Background

2.1. Detections of Felsic or Spectrally Feldspathic Rocks on Mars

2.1.1. Orbital Detections

Orbital VNIR spectra from CRISM have provided widespread detections of plagioclase feldspar on the surface of Mars. These detections are characterized by strong 1.1–1.3 μm absorptions associated with plagioclase feldspar, which we describe as “spectrally feldspathic” after Phillips et al. (2022). Because VNIR spectra are not necessarily diagnostic of rock type, interpreting these detections has been challenging and led to a wide range of hypotheses for the lithologies in which the plagioclase is contained, including extensive anorthositic terrain (Eggers et al., 2021; Phillips et al., 2022, 2025), evolved igneous material similar to intermediate feldspar-rich and felsic rocks generated via fractional crystallization (Carter & Poulet, 2013; Payré et al., 2022; Viviano-Beck et al., 2017; Wray et al., 2013), mafic effusive eruptions containing large plagioclase phenocrysts (Rogers & Farrand, 2022; Rogers & Nekvasil, 2015). Only a few detections are associated with specific geomorphic features, including plagioclase-rich volcanic domes in the northern lowlands (Farrand et al., 2022), and a plagioclase-bearing igneous unit in the Valles Marineris walls (sill, ignimbrite, or porphyritic lava flow; Flahaut et al., 2023; Viviano-Beck et al., 2017). Regardless of the origin of the plagioclase, these detections support a significant crustal volume of plagioclase-bearing rocks, possibly plagioclase-rich (>85 vol.%), much of which were covered by subsequent basaltic volcanism, and support greater crustal compositional variability within the Martian crust than previously thought (Payré et al., 2024; Viviano et al., 2023).

MIR thermal emission spectra provide strong evidence for both anorthositic (Phillips et al., 2022) and evolved rocks (Payré et al., 2022) that are associated with the aforementioned VNIR plagioclase detections. VNIR plagioclase detections in the Syrtis Major caldera have been proposed to be felsic (Wray et al., 2013) and share a genetic connection to nearby and more widespread “dacitic” terrain (Christensen et al., 2005). Other felsic terrains supported by MIR data include granitoid exposures described as quartzo-feldspathic material (Bandfield, 2006; Bandfield et al., 2004) and ancient exposures in the Eridania basin that are consistent with dacitic deposits (Michalski et al., 2024).

2.1.2. Felsic Rocks Interpreted In Situ, in Martian Meteorites, and Through Modeling

Evidence from in situ rover observation, Mars meteorite sample analyses, and petrologic models support the presence of diverse evolved rocks, many of which could have formed early in Mars's history. While exploring Gale crater, the *Curiosity* rover encountered intrusive and extrusive felsic float rocks (Cousin et al., 2017) that have up to ~68 wt.% silica and are rich in plagioclase and K-feldspar, potentially 50–80 vol.% plagioclase for some samples (Cousin et al., 2017; Payré et al., 2017; Sautter et al., 2014, 2015, 2016; Treiman et al., 2016). Many of these igneous rocks exhibited porphyritic to phaneritic textures, including examples of large plagioclase grains (up to 2 cm) embedded in a mafic matrix (Sautter et al., 2015). Ancient (>3.6 Ga) evolved rock fragments similar to quartz monzonite/quartz diorite and granodiorite are also a major component of sedimentary rocks, gravel, and soil in Gale crater, implying a nearby and substantial source of felsic rocks (e.g., Cousin et al., 2017; Mangold et al., 2016; Meslin et al., 2013; Morris et al., 2016; Sautter et al., 2014, 2015). In the floor of Jezero crater, the Mars 2020 rover *Perseverance* has also observed multiple units of igneous rocks, including basaltic andesite lava flows with large plagioclase phenocrysts (B. Horgan et al., 2023; Schmidt et al., 2025; Udry et al., 2023; Wiens et al., 2022).

In martian meteorites, the regolith breccia Northwest Africa (NWA) 7034 contains evolved trachyte and trachyandesite compositions within clasts that are comparable to felsic rocks found in Gale Crater in Santos et al. (2015). Additionally, granitic components were found in the Mars meteorite NWA 6963 (Filiberto et al., 2014, 2018) and monzonitic material has been observed in regolith breccia NWA 7533, a paired meteorite to NWA 7034 (Hewins et al., 2017; Humayun et al., 2013; Malarewicz et al., 2025).

Efforts to model the generation of felsic rocks on Mars have yielded strong evidence that basaltic rocks on Mars could evolve to the composition of the felsic rocks in Gale crater through fractional crystallization and assimilation (Filiberto et al., 2018; Ostwald et al., 2022; Payré et al., 2020). Models show that these rocks could have formed in a range of hydration, temperature, and pressure conditions within the martian mantle, and that felsic rocks may have been produced more frequently on early Mars due to a wetter mantle (Udry et al., 2018). These results also agree with the composition of granitic clasts within NWA 6963 (Filiberto et al., 2014, 2018). Udry

et al. (2018) also argue that felsic rocks on Mars are most similar to those found in intraplate magmatism within oceanic plates (e.g., Iceland, Hawaii) on Earth, rather than continental crust. Alternatively, impact-generated partial melts of early Martian crust (>3.5 Ga) have also been proposed as a petrologic pathway for evolved felsic rocks on Mars (Black & Marchi, 2024; Koepfel et al., 2020), and recent models support early (>4.4 Ga) generation of evolved (>55 wt.% SiO₂) rocks via shallow differentiation of a more hydrous primitive mantle composition (Bernadet et al., 2025).

2.2. Spectral Properties of Plagioclase Feldspar and Felsic Rocks

2.2.1. Mid-Infrared Spectra

MIR thermal emission spectroscopy can be used to accurately determine rock type, mineral abundances, and chemistry for numerous igneous and metamorphic rocks, making it a powerful technique for determining lithologic information of rocks in a lab setting or via remote sensing of rocky planetary surfaces. The MIR wavelength range covers the location of fundamental stretching and vibration modes of silica in minerals common in igneous rocks, enabling the differentiation of different rock types (Conel, 1969; Cooper et al., 2002; Lyon, 1965; Salisbury & Walter, 1989; Wyatt et al., 2001). Key spectral features in this range include the Christiansen feature (CF) and Reststrahlen bands (RB), which vary systematically with silica content and mineral chemistry (Cooper et al., 2002; Farmer, 1974; Feely & Christensen, 1999; Michalski et al., 2005; Rogers & Nekvasil, 2015; Walter & Salisbury, 1989). The CF is an emissivity maximum that occurs at ~8–10 μm (1,300–1,000 cm^{-1}) and shifts to shorter wavelengths with increasing silica polymerization. Thus, CF position can be used to distinguish between mafic, intermediate, and felsic rocks, and more subtle differences like basalt versus basaltic andesite (~7% difference in SiO₂; Wyatt et al., 2001). RB are strong fundamental absorptions from 8 to 14 μm caused by Si-O vibrational modes in silicate minerals (Lyon, 1965; Salisbury & Walter, 1989). The primary RB is an emissivity minimum that occurs between ~9 and 11 μm , at wavelengths just longer than the CF position, and also shifts based on silica polymerization. The wavelength associated with the minimum of the primary RB has been used as a tool to distinguish variability in silica content between feldspathic terrain on Mars (e.g., Payré et al., 2022; Phillips et al., 2022; Rogers & Nekvasil, 2015). The shape and position of the primary RB and additional weaker RBs at longer wavelengths are dependent upon minerals' molecular structure and thus can be used to identify specific types and compositions of silicate minerals (Christensen et al., 2000; Feely & Christensen, 1999; Hamilton & Christensen, 2000; Lyon, 1965; Salisbury & Wald, 1992; Salisbury et al., 1987).

In the MIR, individual minerals composing a rock or mineral mixture (>70 μm) contribute to the overall spectrum proportionally to their surface area via linear mixing. Therefore, quantitative mineral abundances can be derived from the spectral unmixing of thermal infrared whole-rock emissivity spectra (e.g., Feely & Christensen, 1999; Lyon, 1965; Thomson & Salisbury, 1993). With a comprehensive mineral library containing well characterized mineral endmembers, mineral volume percent can be estimated within 5%–15% (Feely & Christensen, 1999; Hamilton & Christensen, 2000; Hamilton et al., 1997; Scudder et al., 2021; Wyatt et al., 2001), bulk oxide weight percent (wt.%) derived from modeled library minerals can be estimated within 10 vol.%, and the corresponding total alkali versus silica (TAS) values plot within or near the appropriate rock type on TAS diagrams (Hamilton & Christensen, 2000; Scudder et al., 2021; Wyatt et al., 2001). Determining the solid solution chemistry of plagioclase feldspar has also been shown to be feasible in the infrared range, but appropriate endmembers are critical for accurate estimations (Feely & Christensen, 1999; Hamilton & Christensen, 2000; Salisbury et al., 1987; Scudder et al., 2021; Wyatt et al., 2001). Spectral unmixing techniques have been applied to Mars orbital data to determine surface rock type and dominant mineralogy using similar unmixing techniques, despite significantly lower spectral resolution compared to a lab setting (Bandfield, 2002; Bandfield et al., 2000; Hamilton et al., 2001).

2.2.2. Visible to Near-Infrared Spectra

Plagioclase feldspar can exhibit a primary absorption band between 1.1 and 1.3 μm , but most commonly near 1.25 μm , caused by electronic transitions in trace amounts (usually <0.5 wt.%) of Fe²⁺ that is incorporated into the crystal structure (Adams & Goulaud, 1978; Adams & McCord, 1971; Adams et al., 1973). We will refer to this as the “1.25- μm band.” Plagioclase with <0.1 wt.% FeO tends to show dramatically weaker absorption at 1.25 μm and a poorly defined band (Adams & Goulaud, 1978). Most commonly, Fe²⁺ + Si⁴⁺ substitutes for 2Al³⁺ and less commonly for Ca²⁺ in tetrahedrally coordinated sites to produce the characteristic 1.25 μm band

(Adams & Goullaud, 1978; Longhi et al., 1976; Lundgaard & Tegner, 2004). The plagioclase band tends to shift to higher wavelengths with increasing anorthite content, or An# (molar $100 \times \text{Ca}/[\text{Ca} + \text{Na} + \text{K}]$), and deepens with increasing iron content (Adams & Goullaud, 1978; Bell & Mao, 1973; Serventi et al., 2013). As An# increases, plagioclase iron content tends to increase as well (Adams & Goullaud, 1978; Barthez et al., 2023; Serventi et al., 2013), and mafic rocks tend to have higher An# and iron content in their plagioclase, because there is more iron available in the melt when minerals begin to fractionate. In contrast, alkali feldspars do not have this feature because Fe^{2+} does not substitute into the crystal structure, and thus are not expected to significantly contribute to the overall whole-rock spectrum. Terrestrial feldspars commonly show OH/H₂O absorptions at 1.4 and 1.9 μm due to fluid inclusions or conversion of plagioclase to clay minerals (Clark et al., 1990; Hunt, 1977).

Compared to other iron-bearing minerals, VNIR plagioclase absorption is relatively weak and is generally thought to require high abundances (>85 vol.%) in order to be confidently detected (Adams & McCord, 1971; Cheek & Pieters, 2014; Cloutis & Gaffey, 1991), or require mafic minerals had to be present at <15 vol.% (Crown & Pieters, 1987; Nash & Conel, 1974). Mafic minerals commonly found with plagioclase, such as pyroxene and olivine, have strong absorptions in the VNIR range caused by ferrous iron incorporated in their crystal structures and effectively mask plagioclase absorption (Burns, 1970, 1993; Burns et al., 1972; Sunshine et al., 1990). Pyroxene typically displays two symmetric absorptions centered near 1 and 2 μm that shift with changing Fe and Ca content (Adams, 1974; Cloutis & Gaffey, 1991; Klima et al., 2007, 2011), and olivine has three overlapping bands near 0.85, 1.05, and 1.15 μm that form a broad, asymmetric absorption that shifts shape and position based on iron content and grain size (Dyar et al., 2009; Isaacson et al., 2014; King & Ridley, 1987; Sunshine & Pieters, 1998). Due to the non-linear nature of VNIR reflectance spectra and the overlap in absorption bands between primary mafic minerals, it can be challenging at times to detect minerals, even qualitatively. For instance, olivine, plagioclase, and Fe-bearing glass can all have absorptions between ~ 1.1 and 2.5 μm , and bimodal mixtures of pyroxene and glass can at times appear indistinguishable from mixtures of pyroxene and olivine or pyroxene and plagioclase (Cheek & Pieters, 2014; B. H. N. Horgan et al., 2014; Serventi et al., 2013).

Most studies seeking to understand the quantity of plagioclase necessary for VNIR detection have focused on mixing powders of plagioclase with mafic minerals, like pyroxene and olivine, the major constituents of basaltic terrains on rocky planetary surfaces like the Moon's maria (e.g., Adams & McCord, 1971; Cheek & Pieters, 2014; Cloutis & Gaffey, 1991; Serventi et al., 2013), and used small grain size (<150 μm) to simulate spectral mixing relationships on regolith-covered airless bodies. However, this is not necessarily representative of terrains on Mars, where regolith-free bedrock surfaces are more abundant.

In powdered mixtures, fine grain sizes tend to produce more reflectance (higher albedo) and decrease spectral contrast, and thus are spectrally dominant in mixtures with multiple grain sizes (e.g., Mustard & Hays, 1997; Pieters et al., 1993; Serventi & Carli, 2017). Compared to their smaller counterparts, larger grains have less surface area and tend to produce deeper absorption bands due to higher spectral contrast (e.g., Adams & Filice, 1967; Carli et al., 2015; King & Ridley, 1987) until they begin to approach a maximum band depth near 1 mm diameter and then significantly shallow (Craig et al., 2008; Harloff & Arnold, 2001). Lab VNIR measurements of a coarse ($\sim 840 \mu\text{m}$) mixture of plagioclase and pyroxene show a strong 1.25 μm band, even at $\sim 50\%$ mafic content (Rogers & Nekvasil, 2015). Though only one type of pyroxene was tested, these results contradict previous studies that asserted 15 vol.% mafics would obscure the plagioclase band in VNIR spectra. In this case, the larger plagioclase grain size reduces the likelihood of photon interaction with more strongly absorbing pyroxene grains, implying coarse-grained plagioclase is detectable at significantly lower abundance than typically thought.

In whole rocks, both grain size and texture strongly influence plagioclase absorption band strength, especially in the presence of mafic minerals. Coarsely crystalline rocks display stronger absorption bands than fine-grained counterparts (e.g., pyroxene bands in gabbro vs. basalt; Carli et al., 2015), as do phenocrysts within a holocrystalline groundmass. Recent VNIR measurements of plagioclase-phyric basalts show evidence of a 1.25 μm band despite the presence of pyroxene and olivine (Barthez et al., 2023, 2026), suggesting that plagioclase may be detectable in effusive rocks under specific circumstances, even at ~ 20 wt.% plagioclase, and that grain size is a key factor in detectability. In addition, studies of mafic effusive rocks show that fine-grained groundmass, welded mineral grains, opaque minerals (i.e., oxides), and aqueous alteration reduce spectral contrast, flattening whole-rock spectra and erasing both plagioclase and stronger mafic bands (Carli & Sgavetti, 2011; Cloutis et al., 1990b; Moroz & Arnold, 1999; Scudder et al., 2021).

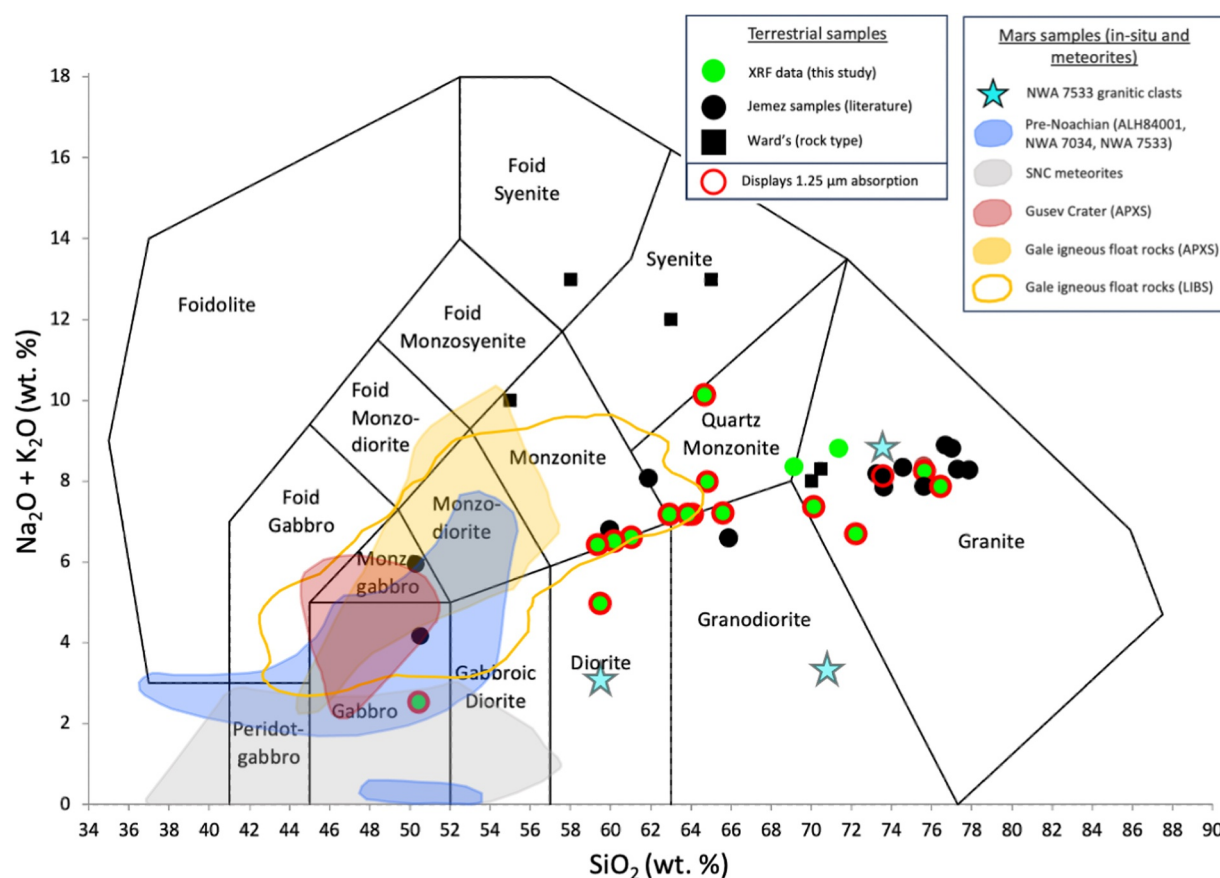


Figure 1. Total alkali-silica classification diagram (Middlemost, 1994) for the samples in this study. Green circles: bulk chemical data obtained during or prior to this study. All points with red circles indicate samples with a 1.25 μm VNIR absorption band in bulk spectra. Black circles: Jemez Mountains (Valles Caldera) samples; chemical data derived from equivalent units in literature (Broxton et al., 2007; Gardner et al., 1986; Heiken et al., 1986; Loeffler et al., 1988; Rowe et al., 2007; Self et al., 1988; Wolff et al., 2024; Wu et al., 2020). Black squares: plotted based on rock type (Le Maitre et al., 2005) defined on the Ward's Science website where they were obtained. Shaded and outlined regions (after Payré et al., 2024; Schmidt et al., 2025) represent martian igneous compositions observed in situ (red and orange; Berger et al., 2020; Brückner et al., 2003; Cousin et al., 2017; P. H. Edwards et al., 2017; Ming et al., 2008; Sautter et al., 2015), and through analyses of martian meteorites (Hewins et al., 2017; Humayun et al., 2013; Santos et al., 2015; Udry et al., 2020; Wittmann et al., 2015). Blue stars: chemical data derived from granitic clasts in Mars meteorite NWA 7533 (Malarewicz et al., 2025).

Thus, in the case of both whole rock and powdered mixtures, it seems a larger grain size is critical for VNIR plagioclase detection in the presence of mafic minerals. Eruptive products bearing large plagioclase crystals are experimentally plausible on Mars, especially in wet melts, and detections of evolved rock types support magmatic fractionation throughout Martian history which would allow higher water content (Ruff et al., 2006; Sautter et al., 2014). However, studies to date have not included coarse-grained plagioclase-bearing felsic rocks or a wide range of plagioclase-phyric rocks, leaving uncertainty in the detectability of plagioclase in VNIR spectra of rocks that could plausibly be exposed on Mars's surface. Until a spectral data set from a wider range of rock types is produced, the potential diversity of Mars lithologies expressed in orbital spectral data cannot be accurately or confidently evaluated.

3. Methods and Sample Suite

Our sample set of 42 rocks (Figure 1, Table 1) was chosen to represent broad diversity in plagioclase-bearing and felsic rocks to investigate how petrologic properties modify VNIR spectra. We first collected bulk VNIR reflectance spectra and TIR emissivity spectra for all samples. 19 samples showed a 1.25 μm absorption band potentially consistent with plagioclase which we used to define spectral groups, and these were then downselected to undergo more detailed analyses. We collected high-resolution hyperspectral VNIR scans of 17 of these samples to determine how individual minerals contribute to overall bulk VNIR spectra. 13 samples representative of

Table 1
Basic Information for All Samples in This Study for Which Visible to Near Infrared (VNIR) Data Was Collected

Sample	Type	# of samples	~SiO ₂ wt. %	Texture
Tonalite ^{a,b,c,d}	Intrusive	3	64–72	Coarse crystalline
Monzonite ^{a,b,c,d}	Intrusive	2	64	Coarse crystalline
Granodiorite ^{a,b,c,d}	Intrusive	6	60–65	Coarse to medium crystalline
Granite ^{a,b,c,d}	Intrusive	5	70–75	Coarse to fine
Basalt ^{a,b,c,d}	Extrusive	4	46–50	Porphyritic
Andesite/basaltic andesite ^{a,b}	Extrusive	3	54–61	Porphyritic to aphanitic
Dacite ^{a,b}	Extrusive	1	64	Porphyritic
Ignimbrite ^{a,b}	Extrusive	3	70	Coarse clastic
Rhyolite ^{a,b}	Extrusive	11		Porphyritic to sparsely porphyritic, glassy, porphyritic glass (obsidian), tuffaceous
Trachyte ^a	Extrusive	1	61–69	Porphyritic
Syenite ^a	Intrusive	1	56	Coarse
Malignite ^a	Intrusive	1	56	Coarse

Note. Corresponding chemical information for these rocks are shown in Figure 1. Letters indicate data was obtained for at least one sample. a: VNIR and TIR; b: XRF; c: XRD; d: EPMA plagioclase chemistry.

spectral diversity were selected for detailed microscopic and chemical analyses to assess spectral-lithologic connections, controls on 1.25 μm band detections, and plagioclase abundance. Each analysis is described in more detail starting in Section 3.2.

3.1. Justification of Terrestrial Samples for Mars Comparison

The goal of the sample suite is to capture the possible petrologic diversity of felsic and plagioclase-bearing rocks on Mars. One challenge for Earth-Mars comparisons of evolved igneous rocks is that the majority of modern felsic rocks on Earth are formed as hydrous melts within subduction zones, whereas a lack of widespread plate tectonics on Mars means that martian melts are expected to be comparatively anhydrous (Filiberto & Dasgupta, 2011; Filiberto & Treiman, 2009; Rapp et al., 2013; Usui et al., 2012). The argument for anhydrous melts is supported by the dearth of hydrous primary minerals like biotite or amphibole in felsic rocks observed on Mars (Cousin et al., 2017; Sautter et al., 2016). However, some alkaline rocks in Gale and Gusev craters have been hypothesized to be the result of fractionation of more hydrous magmas, potentially suggesting a metasomatized mantle source (McSween, 2015; Michalski et al., 2021; Udry et al., 2018).

Thus, our sample suite contains both rocks formed from more common hydrous terrestrial magmas as well as those from potentially more typical Mars-like anhydrous melts. Plagioclase-phyric basalt, monzonite, granodiorite, and granite are similar to some of the hypothesized petrologies of Mars feldspathic terrain. Our tholeiitic basalt sample is a product of rifting/crustal melting and bears large (>1 cm) plagioclase grains, an excellent analogue to test hypothesized Mars megacryst lavas (i.e., plagioclase-phyric; Flahaut et al., 2023; Rogers & Nekvasil, 2015). Some samples (monzonite, granite) are quartz and plagioclase-dominated, similar to hypothesized felsic crustal rocks (Rogers & Farrand, 2022; Wray et al., 2013). The relatively anhydrous ferroan granite is likely a differentiate of a tholeiitic parent melt (Eddy et al., 2016), and thus was likely formed in a drier setting closer to expected Mars mantle conditions (Filiberto & Treiman, 2009; Rapp et al., 2013; Usui et al., 2012). While we do not have anhydrous equivalents for our granodiorites, tonalites, and monzonites, the samples are still highly useful for assessing the detectability of plagioclase in coarse-grained felsic lithologies because they are similar rock types to proposed evolved plutonic rocks on Mars. In the discussion, we carefully consider the spectral influence of hydrous minerals in our samples. Additionally, these are strong analogs for any hydrous felsic rocks on Mars, if present, that will aid in future searches for primary hydrous minerals.

3.2. VNIR Whole-Rock Spectra

Bulk VNIR reflectance spectra for 42 samples were collected at Purdue University using an Analytical Spectral Devices FieldSpecPro 3 spectrometer with contact probe attachment. The spectrometer measures reflectance between 0.35 and 2.5 μm at standard incidence/emission angles of $0^\circ/30^\circ$ with a spectral resolution between 3 and 10 nm, resampled to 1 nm. This instrument has a similar spectral range and resolution to CRISM (0.4–3.9 μm , 6.55 nm sampling; Murchie et al., 2007). Each spectrum is the average of 60 scans collected over a $\sim 3\text{ cm}^2$ area (2 cm diameter contact probe) and calibrated with a white reference prior to measurement. Measurements were taken from fresh interior surfaces to minimize the influence of alteration on spectra. For each sample, spectra from three spots were collected and averaged to ensure that the mineralogical heterogeneity of coarse-grained rocks was captured. To ensure the averaging method did not introduce any bias, we calculated spectral parameters for individual spectra and compared them to the averaged spectrum and did not see significant change in the parameters. We acknowledge translating this data to an outcrop scale similar to CRISM data is challenging given there may be greater variability at outcrop scale, but comparing hand samples to orbital data is an effective and commonly practiced method to evaluate a wide variety of samples to contextualize orbital measurements.

3.3. High-Resolution Spectral Scans

To understand the relationship between the bulk spectra and individual mineral components, high spatial resolution VSWIR scans were acquired for a subset of 17 samples at the California Institute of Technology using a Headwall Photonics, Inc. (Fitchburg, MA, USA) imaging spectrometer system. The instrument contains two co-boresighted sensors (f/2.5 aperture vertical slit cameras): VNIR (0.4–1.0 μm) and SWIR (1.0–2.5 μm). Samples were illuminated by a halogen slit lamp and moved at a constant rate under the spectrometer to build an image cube. Data were corrected to reflectance by subtracting a dark current measurement and then calibrated pixel-by-pixel to Spectralon (Labsphere), correcting for the absolute reflectance properties of the standard. Image cubes at resolutions of up to $\sim 80 + 250\text{ }\mu\text{m/pixel}$ (VNIR + SWIR) can resolve individual mineral grains (Greenberger et al., 2015). Because these 17 samples are either coarse crystalline intrusive rocks or effusive mafic samples with plagioclase phenocrysts, they are well above the resolution required to measure spectra from individual mineral grains with this imaging spectrometer. All rocks without visible plagioclase grains also did not have a 1.25 μm absorption in bulk VNIR spectra, so they were excluded. These 17 samples are representative of the full sample set's lithologic range (Figure 1, circles). Spatially resolved spectra were compared to bulk spectra to determine how other minerals present as phenocrysts or groundmass affected the detection of the $\sim 1.25\text{ }\mu\text{m}$ absorption in a whole-rock spectrum. Mineral endmember spectra (Figure 2) aided in mineral identification.

Scanned spectral cubes of the samples were processed in IDL. Average spectra were extracted from contiguous regions of interest over specific minerals or mineral groups. To test a variety of spectral parameters to highlight different types of mineral absorptions, we calculated the integrated band depth (IBD) at 1.3, 1.9, 2.2, 2.25, and between 2.3 and 2.35 μm , where the area is calculated between the spectrum and a linear continuum between tie points at shoulders on either side of the given absorption feature. The band depth at 2.33 μm (BD2330) was calculated by subtracting the reflectance from the continuum at that point. These parameters and their intended use are listed in Table 2, and will be referred to by those names moving forward (e.g., 1.3 μm IBD is referred to as IBD1300). These band parameters emphasize Fe^{2+} absorption and $>2\text{ }\mu\text{m}$ OH and metal-OH overtones and combination bands in our samples. IBD1300 was particularly useful to highlight plagioclase absorption and mineral grain boundaries among groups of light toned, felsic minerals (quartz, K-feldspar). We calculated the slope between 1.2 μm and 2.1 μm (SWIR slope parameter) to highlight mafic hydrous minerals which consistently exhibit strong spectral red-slopes compared to other minerals, meaning a steep positive slope from shorter to longer wavelengths. The bounds of the IBD's can be found in Table S1 in Supporting Information S1.

We generated composite images to highlight mineralogical variability across each sample by assigning spectral parameters to red, green, and blue (R, G, B) channels. Spectral parameter images best suited for discriminating minerals in felsic samples are defined in Table 3. Our preferred spectral parameter color composite for the scans was red: IBD 1300, green: SWIR slope, blue: IBD 2350, where red typically indicates plagioclase, green/yellow indicates hydrous mafic minerals, and black or dark colors indicate felsic minerals (PM spectral parameter combination). In cases where samples had no $\sim 2.3\text{ }\mu\text{m}$ absorption the IBD 2350 parameter was replaced with IBD 1900 to emphasize hydration.

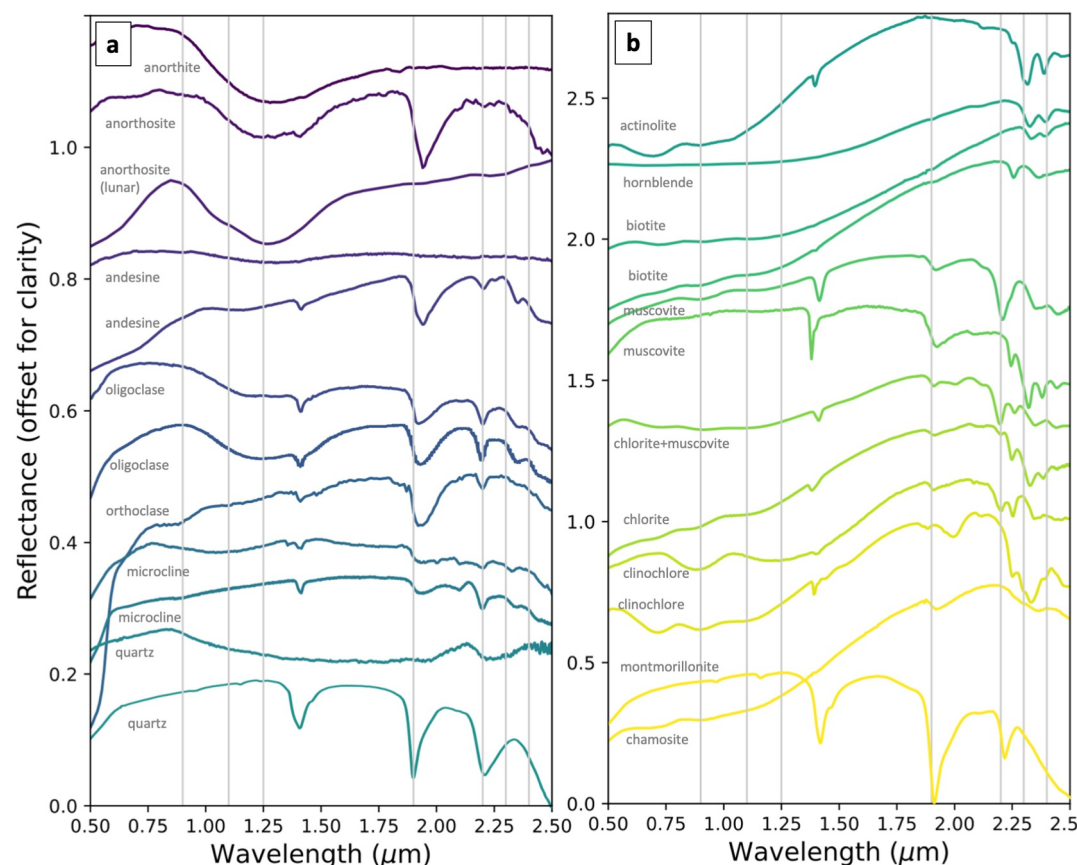


Figure 2. Laboratory reflectance spectra of minerals relevant to this study and anorthosite. (a) Plagioclase can exhibit a characteristic absorption at $\sim 1.25 \mu\text{m}$ due to the substitution of Fe^{2+} in the crystal structure. Felsic minerals (quartz, K-feldspar) do not have strong absorption features in the visible to near-infrared range other than hydration features (1.4 , $1.9 \mu\text{m}$) from water inclusions or alteration. (b) Primary hydrous mafic minerals and secondary minerals produced by alteration show complex absorptions at $>2 \mu\text{m}$, some of which are diagnostic, and also can have a significant spectral red-slope. Sample IDs and spectra can be found in the supplemental data repository.

Other spectral parameter images attempted, but not useful across the entire sample set, are shown in Figures S1–S17 in Supporting Information S1. For basalts, we used $R = \text{IBD1300}$, $G = \text{IBD1090}$, $B = \text{IBD2250}$, and $R = \text{IBD1300}$, Green = SWIR slope, Blue = IBD2250 (Figures S1–S4 in Supporting Information S1) which distinguished small olivine phenocrysts intergrown with plagioclase. We used $R = \text{IBD1300}$, $G = \text{SWIR slope}$, $B = \text{IBD1900}$ for samples without strong $>2 \mu\text{m}$ absorptions, which we define as the plagioclase/mafic/hydration (PMH) spectral parameter combination. For granites lacking any plagioclase absorption, we used $R = \text{IBD1900}$, $G = \text{SWIR slope}$, $B = \text{IBD2350}$ (Figure S17 in Supporting Information S1), defined as the hydration/mafic (HM) spectral parameter combination.

Using these spectral parameter images to identify spectrally homogeneous zones, we extracted representative mineral grain spectra from all major components. Mineral grains larger than the scan resolution and mixed matrix with grains below the scan resolution are both considered spectrally homogeneous zones. Regions of interest were drawn within individual mineral grains, mineral groups, and groundmass (basalts only), from which average spectra were obtained. We selected minerals at similar foci (i.e., same elevation); edges, steep surfaces, and shadows were avoided to minimize spectral effects and noise from surface topography. To mitigate slope effects and provide the best comparison to planetary surfaces, we obtained and analyzed spectra from natural surfaces of the samples. Note that sawed surfaces of some granodiorites and granites exhibited an exaggerated spectral blue-slope (a negative slope from shorter to longer wavelengths), but their band centers did not change. All RGB spectral parameter images and extracted spectra can be found in the supplemental information.

Table 2
Names, Interpretations, and Applications of Parameters Used for Interpreting Spectral Data

Parameter	Interpretation	Application
SWIR slope	Enhanced SWIR red slope	Emphasizes amphibole and chlorite VNIR spectral scans of felsic rocks (Figure 7)
IBD1090	Fe ²⁺ absorption (e.g., Burns, 1993)	Emphasizes pyroxene VNIR spectral scans of basaltic rocks (Figure 8)
IBD1300	Fe ²⁺ absorption (Adams & Goullaud, 1978)	Emphasizes plagioclase VNIR spectral scans of basaltic and felsic rocks (Figures 7 and 8)
IBD1900	H-O-H combination bands (e.g., Clark et al., 1990; Hunt, 1977)	Emphasizes hydration in minerals VNIR spectral scans of basaltic and felsic rocks (Figures 7 and 8)
IBD2200	OH combination bands (e.g., Bishop et al., 2002, 2008; Hunt & Ashley, 1979)	Emphasizes muscovite, montmorillonite VNIR spectral scans of felsic rocks (Figure 7)
IBD2250	OH combination bands (e.g., Bishop et al., 2008; Clark et al., 1990; King & Clark, 1989)	Emphasizes chlorite/biotite in VNIR spectral scans of felsic rocks (Figure 7)
IBD2350	Fe/Mg-OH combination (e.g., Bishop et al., 2008; Clark et al., 1990; Hunt, 1977; Mustard, 1992)	Emphasizes chlorite, amphibole in VNIR spectral scans of felsic rocks (Figure 7)
BD2330	Fe/Mg-OH combination (e.g., Bishop et al., 2008; Clark et al., 1990; Hunt, 1977; Mustard, 1992)	Emphasizes rocks dominated by hydrous minerals in band parameter analysis (Figure 5)

After extracting the average spectra from ROIs of the scanned samples, we derived additional band parameters from these spectra and the bulk whole-rock spectra. To perform detailed analyses on the 1.25 and >2 μm absorptions, the slope of the spectral continuum was removed (e.g., Clark & Roush, 1984). For each mineral and whole-rock spectrum, we performed an initial continuum removal first to maximize the area of the 1.25 μm band and determine its band center, depth, and asymmetry (Bennett et al., 2016; B. H. N. Horgan et al., 2014). The slope of the continuum is first estimated with two linear segments fitted to fixed end points at 1.0, 1.7, 2.15, and 2.7 μm that together form a linear convex hull. A new continuum is then estimated by fitting two linear segments to the original spectrum between these tie points. The continuum is then suppressed by dividing the original spectrum by the convex hull formed by these segments. The spectra were smoothed with a boxcar average of width ~ 0.25 μm (three channels) prior to continuum removal and spectral analysis to reduce the effect of noise in the data. The longer wavelength absorptions >2 μm were fit separately with tie points at 1.8 and 2.6 μm to determine the 2.3 and 2.4 μm bands (J. L. Bishop et al., 2008). The BD2330 spectral parameter was calculated by subtracting the reflectance value at 2.33 μm from the continuum. We also employed a band ratio of 1.7/1.1 μm in the whole-rock band parameter analysis because it better differentiated rock types than the SWIR slope parameter.

Comparison of whole-rock and individual mineral spectra required measurements from two different instruments. To validate this comparison, an average spectrum was obtained from a scanned sample ROI with the same dimensions as the collection window of the ASD spectrometer used for whole-rock measurement. We found the band centers from the scanned spectrum and the bulk whole-rock spectrum to be the same, which lent confidence that comparison of band centers was without significant error. Band center is the only spectral parameter used to compare bulk spectra and individual mineral spectra.

Table 3
Names and Interpretations for Primary Spectral Parameter Images

Spectral parameter image	Parameter combination	Interpretation of colors
Plagioclase/mafic (PM)	Red = IBD1300, Green = SWIR slope, Blue = IBD2350	Red: plagioclase; blue/black: quartz, K-feldspar; green/yellow: hydrous mafic minerals
Plagioclase/mafic/hydration (PMH)	Red = IBD1300, Green = SWIR slope, Blue = IBD1900	Red: plagioclase; dark green: quartz, K-feldspar; bright green/blue: hydrous mafic minerals
Hydration/mafic (HM)	Red = IBD1900, Green = SWIR slope, Blue = IBD2350	Orange: felsic minerals; black/dark green: mafic minerals

3.4. Thermal Emission Spectra

TIR emission spectra for 41 samples were acquired at the Arizona State University (ASU) Mars Space Flight Facility using a Nicolet iS50R FT-IR spectrometer modified to measure emitted energy, the setup and calibration of which is similar to that described by Ruff et al. (1997). Prior to measurement, each sample was rinsed with isopropyl alcohol, dried, then placed in an oven for at least 2 hr prior to measurement. Because all samples measured were rinsed whole-rock hand samples, we expect the effect of clinging fines (reduced spectral contrast) was mitigated.

We created a new endmember mineral library called “felsic_suite” derived from the ASU SpecLib (Christensen et al., 2000) and previously published sources to model our emissivity spectra. The minerals were chosen to most accurately model plagioclase abundance and omit minerals that were not present based on XRD analysis. General igneous mineral libraries in the ASU SpecLib database and a more refined igneous library (Scudder et al., 2021) were attempted but yielded erroneous modeling of sheet silicates (not actually present), K-feldspar (overestimated), and some plagioclase endmembers (incorrect chemistry). In particular, when anorthoclase was included, it would account for all the feldspar in the deconvolution model of granodiorites, so it was omitted. The deconvolution still has some difficulty modeling K-feldspar with our mineral library (see Section 4.3 for further discussion), but the TIR models provide reasonable estimates of mineral abundances that are consistent with past studies (5%–15%; e.g., Feely & Christensen, 1999; Hamilton & Christensen, 2000; Scudder et al., 2021).

MIR sample spectra were convolved with THEMIS bandpasses to mimic what the spectra would look like if observed with that instrument (Christensen et al., 2000). Then the band center (sensitive to silica wt.%) and band shape (related to overall mineralogy) were calculated using a spline fit minima (Phillips et al., 2022; Rogers & Nekvasil, 2015).

3.5. Petrologic Analyses

Thirteen samples were selected for detailed petrologic and microscopic analyses to better understand how their bulk composition, modal abundances, plagioclase chemistry, and mineral grain sizes connect to the spectral character of their host rock (Table 4). We selected samples that were spectrally representative of the sample set in bulk VNIR data, primarily those that display a 1.25 μm absorption, and a few that do not produce a 1.25 μm absorption yet are plagioclase-rich and have similar lithologies to rocks that do produce an absorption (e.g., granites, plagioclase-phyric basalt). Samples included were one plagioclase-phyric basalt, two tonalites, two monzonites, five granodiorites, one granite-granodiorite, and two granites.

3.5.1. Quantitative X-Ray Diffraction

The 13 samples with petrologic analyses were also sent to Activation Laboratories Ltd. in Lancaster, Ontario for XRD analyses. A portion of each pulverized sample was mixed with corundum and loaded into a standard holder. Corundum was added as an internal standard. The X-ray diffraction analysis was performed on a Bruker D8 Endeavor diffractometer equipped with a Cu X-ray source and operating at the following conditions: 40 kV and 40 mA; range 4–70 deg 2 θ ; step size 0.02 deg 2 θ ; time per step 0.5 s; fixed divergence slit, angle 0.3°; sample rotation 15 rpm. The PDF4/Minerals ICDD database of over 177,000 minerals was used for mineral identification. The quantities of the crystalline mineral phases were determined using the Rietveld method (Rietveld, 1969). The Rietveld method is based on the calculation of the full diffraction pattern from crystal structure data. The amounts of the crystalline minerals were recalculated based on a known percent of corundum and the remainder to 100% was considered X-ray amorphous material. It is estimated that the minerals present in less than 2% of the sample might not be detected. The biotite measured here encompasses any minerals detected in the biotite group. The XRD results were compared to TIR-derived mineral abundances, and used to assess VNIR spectral parameters and plagioclase detection limits. Mineral abundances in wt.% were converted to vol.% using representative mineral densities and normalized to 100 vol.%. Mineral densities used in the conversion are included in Table S2 in Supporting Information S1 and steps for the description of the conversion and choice of mineral densities are described in Text S2 in Supporting Information S1. The conversion caused only minor change ($\leq 0.7\%$; Table S3 in Supporting Information S1) in plagioclase content for all but the basalt (3.1%).

Table 4*Summary of Key Information for the Subset of 13 Samples for Which Imaging Spectroscopy and Microscopy Data Was Acquired*

Sample ID	Drive 2	NCMF22-SK65	NCMF22-SK67	ME-046	ME-048	DO-008	DO-010	DO-013	SR22-ML-18	SR21-ML28	SR21-ML24	SR21-ML27	DO-021
Rock Type	Basalt	Tonalite	Tonalite	Monzonite	Monzonite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granite-granodiorite	Granite	Granite	Aplite dike
Bulk SiO ₂ wt. %	50.5	64.8	72.3	64.1	63.9	65.6	60.2	63.0	64.7	70.1	75.6	76.5	75.6
Bulk-rock Band Center	1.04	1.12	1.20	1.16	1.29	1.24	1.23	1.26	1.15	1.26	1.40	1.30	1.27
Plagioclase Band Center	1.29	1.20 ^a	1.40 ^a	1.28	1.29	1.30	1.30	1.29	—	1.28	1.40 ^a	1.32	1.31
Plagioclase An#	90	37	33	41	47	47	47	46	16	42	25	24	39
Plagioclase FeO wt. %	0.462	0.0407	0.0202	0.236	0.130	0.180	0.156	0.180	0.148	0.186	0.119	0.141	0.172
Plagioclase	62.7	45.9	49.2	47.5	40.7	35.5	47.7	34.4	51.7	38.0	31.2	31.8	24.3
Quartz	—	35.5	37.2	23.1	25.5	29.5	20.7	21.5	11.8	31.4	43.2	35.7	38.8
K feldspar	—	7.8	7.4	19.7	17.2	24.8	11.4	26.1	30.5	23.4	23.7	30.2	33.3
Amphibole	—	—	—	5.4	7.7	4.6	9.3	8.5	5.5	3.3	—	—	—
Biotite	—	4.7	4.7	0.6	7.7	3.5	9.2	1.0	0.0	2.3	1.0	0.6	0.4
Muscovite	—	6.0	—	—	—	—	—	—	—	—	—	—	—
Chlorite	—	0.5	1.4	3.6	1.3	2.1	1.7	8.6	0.5	1.6	0.9	1.6	3.2
Augite/Diopside	21.4	—	—	—	—	—	—	—	—	—	—	—	—
Forsterite	4.8	—	—	—	—	—	—	—	—	—	—	—	—
Amorphous	11.1	—	—	—	—	—	—	—	—	—	—	—	—

Note. Data shown are derived from bulk VNIR spectra (whole-rock band center), VNIR spectral scans (plag band center), XRF (SiO₂ wt. %), XRD (wt. % converted to vol. %), EPMA (plagioclase FeO wt. % and An#). All mineral abundances here are reported in vol. %. ^aSignificant uncertainty due to challenges in identifying plagioclase in spectral scans.

3.5.2. Bulk Chemistry

To acquire silica content and alkalinity, X-Ray Fluorescence data for 16 samples was obtained from Actlabs Ltd in Ancaster Ontario and one sample with a Olympus Vanta M Series portable X-Ray Fluorescence (Bedford et al., 2024). The XRF data for the 16 samples from Valles Caldera were obtained from matching our samples' coordinates to the USGS geologic map of the region and to the corresponding units in the literature (Broxton et al., 2007; Gardner et al., 1986; Heiken et al., 1986; Loeffler et al., 1988; Rowe et al., 2007; Self et al., 1988; Wolff et al., 2024; Wu et al., 2020). When collected, our Valles samples were labeled with the same common unit names found in the geologic map and literature, enabling further corroboration.

3.5.3. Mineral Chemistry

Plagioclase chemistry was obtained for 13 samples at the EPSC Microanalysis Facility at Washington University in St. Louis using the JEOL JXA-8200 scanning electron microscope for electron-probe microanalyses (EPMA). It is equipped with five wavelength-dispersive spectrometers and a silicon-drift energy-dispersive spectrometer. Flat and polished thin sections were coated with a 22 nm layer of carbon using a high-vacuum carbon evaporator. For each thin section, at least 10 plagioclase grains were analyzed using an accelerating voltage of 15 kV, a beam current of 25 nA, and a 20 μm beam diameter to measure plagioclase phenocrysts. The elements analyzed included Na, Mg, Al, Si, Mn, Fe, K, P, Ni, Cr, Ti, Ca, S, and Co. Each plagioclase grain interior and rim was probed, and for some larger grains 3–4 points were taken radially outward from the center. Some samples had plagioclase grains with light and dark toned interiors, both of which were probed to determine any compositional variability within the grain boundaries.

We measured trace iron on multiple spectrometers (3 and 5; 60 s run times) and summed the intensities to create a composite k-ratio. Elba hematite was used as the iron standard, a high concentration stoichiometric iron standard routinely used. Background corrections were made using the mean atomic number background correction standard for the lab (all standards that do not contain the element of interest; for iron, synthetic forsterite, among others, was used). For each element, we checked line fit plots to make sure they were strong fits to lab standards. The iron detection limit for our runs is ~ 70 ppm, and the iron content observed in the plagioclase grains across all samples was well above this limit.

Ahead of the EPMA analyses, we generated back-scattered electron (BSE) and secondary electron (SE) imaging and energy-dispersive X-ray spectroscopy (EDS) elemental mapping in the Hitachi TM4000 Plus bench-top SEM at Purdue University to provide preliminary identification of plagioclase grains. We also used EDS maps to investigate chemical composition of oxide grains.

3.5.4. Grain Size

Approximate grain sizes were determined by measuring grain dimensions via thin section and SEM images. Among the 13 samples that underwent more detailed analyses, the 12 intrusive rocks are equigranular. Of these, 11 intrusive rocks are phaneritic and possess >0.75 mm phenocrysts, typically 1–5 mm, with some examples up to ~ 1 cm. We define these as coarse-grained. One intrusive rock (aplite) is predominantly phaneritic and has phenocrysts from ~ 0.15 to 0.75 mm which we define as medium-grained. The porphyritic basalt has phenocrysts >1 mm and up to ~ 1 cm contained in a fine-grained (<0.25 mm) groundmass. Crystals <0.25 mm are defined as fine grained.

4. Results

4.1. Sample Properties Relevant to Spectral Interpretation

Here we provide a summary of petrologic data derived from our analyses that exhibits primary control on the spectral character of the samples (summarized in Table 5). Additional data can be found in Text S1 in Supporting Information S1 data repository. The sample suite spans basaltic to felsic compositions (50.5–76.5 wt.% SiO_2 ; Figure 1), but the sample subset of 19 rocks that exhibited absorptions at or near $1.25 \mu\text{m}$ is dominated by intermediate–felsic intrusive rocks (60.2–76.5 wt.% SiO_2) and includes only two mafic rocks (plagioclase-phyric basalt). Most intrusive samples are coarse-grained, whereas the two basalts contain millimeter- to centimeter-scale plagioclase phenocrysts in a fine-grained groundmass. XRD analyses of 13 samples yielded a plagioclase feldspar modal abundance range of 24.7–59.6 vol.%. The mafic mineral content varies from 2.10 to 29.7 vol.%; basalt is highest at 29.7% combined olivine and pyroxene vol.%. Among the remaining 12 samples (all intrusive), hydrous minerals (amphibole, biotite, muscovite, chlorite) compose 2.10–22.8 vol.%, with amphibole and biotite being most abundant. Plagioclase iron content for the 13 samples ranges from 0.021 to 0.46 wt.%, including two tonalites with depleted plagioclase iron content (0.021–0.040 wt.%); other samples have substantially higher iron content. Plagioclase compositions span An_{16-90} , although nine of 13 samples fall in the andesine range of An_{30-50} (Figure 3). The plagioclase-phyric basalt is by far the highest at An_{90} , consistent with anorthite, and three granites fall below 25 $\text{An}\#$ in the oligoclase range. Together, these samples span a broad range of plagioclase abundance, chemistry, mafic mineral content, and grain size, providing an opportunity to evaluate how each parameter influences whole-rock VNIR spectra.

4.2. VNIR Spectra

4.2.1. Whole-Rock

Of our original 42 rocks, 19 display absorption bands at or near $1.25 \mu\text{m}$ (Figure 4), and intrusive, coarse-grained, plagioclase-bearing rocks commonly exhibit a 1.20 – $1.35 \mu\text{m}$ absorption band (Figure 4a). The $\sim 1.25 \mu\text{m}$ absorption band shapes and positions of granodiorites (34.0–51.6 vol.% plag; 60.2–65.6 wt.% SiO_2) are most similar to plagioclase absorption bands. Intrusive rocks also typically exhibit complex absorptions between ~ 2.2 and $2.4 \mu\text{m}$, most prominent in tonalites (45.8–49.1 vol.% plag; 64.8–72.3 wt.% SiO_2), and weak or absent in granites (24.7–32.1 vol.% plag, 75.6–76.5 wt.% SiO_2). These $>2 \mu\text{m}$ bands are most commonly caused by primary hydrous minerals such as mica and amphibole, and secondary clay minerals, most likely chlorite and montmorillonite. Specific mineral identifications are expanded upon in Section 4.2.3. Hydration bands at 1.4 and $1.9 \mu\text{m}$ are

Table 5
Summary of Key Spectral Parameters and Lithologic Characteristics of Spectral Groups

Spectral group	Spectral features defining group	Rock type	Mineral grain size	Plagioclase abundance (wt.%) ^a	Plagioclase FeO % ^a	Mafic mineral abundance (wt.%) ^a
Plagioclase-dominated (G1 in Figures 4 and 7)	Strong ~1.25 μm bands closely resembling plagioclase absorption Weak to moderate 2.3–2.35 μm band Neutral spectral slope	Granodiorite (5) Monzonite (1) Granite-granodiorite (1)	>0.75 mm, 1–3 mm frequent	34.0–46.5	0.130–0.186	9.3–22.8
Hydrous mafic-dominated (G2 in Figures 4 and 7)	Moderate ~1.25 μm band differs from plagioclase in spectral slope and band center Strong 2.3–2.35 μm band Steep spectral red-slope between 1.1 and 1.8 μm	Tonalite (3)	>0.75 mm, >1 mm frequent	45.8–49.2	0.0202–0.0407	6.9–11.8
Weak absorption (G3 in Figures 4 and 7)	Weak ~1.25 μm band Weak or absent 2.3–2.35 μm band Steep red-slope <0.9 μm and blue-slope from 0.9 to 2.5 μm	Aplite (1) Granite (3) Granodiorite (1)	Aplite: ~0.15–0.75 mm Others: >0.75 mm, majority >2 mm, occasional >1 cm	24.7–51.6	0.119–0.172	2.1–7.2
Ambiguous (G4 in Figures 4 and 7)	~1.25 μm band shifted to shorter wavelengths or overlap with 1 μm pyroxene and olivine absorption 2.3–2.35 μm band is weak or absent except for one sample Neutral or weak spectral blue-slope	Plagioclase-phyric basalt (2) Glassy dome rock (1) Monzonite (1)	Basalt: groundmass <250 μm phenocrysts >1 mm and up to 1 cm	47.4–59.6	0.236–0.462	13.0–29.7
From subset of spectral group members.						

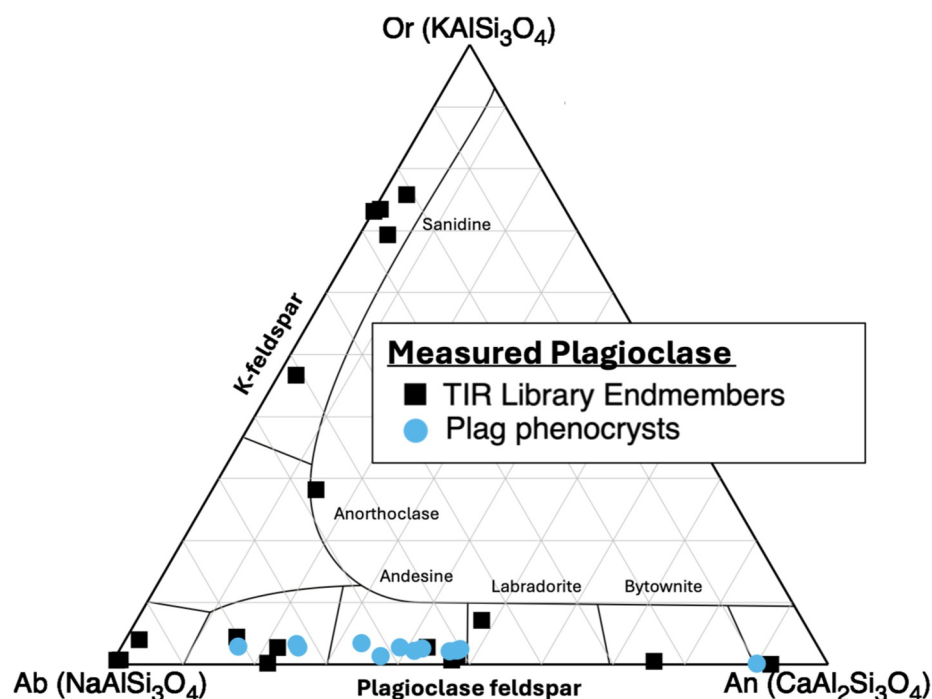


Figure 3. Electron-probe microanalyses-measured plagioclase feldspar compositions for 13 samples, most of which are in the andesine to oligoclase range (blue circles). TIR feldspar endmembers used for linear deconvolution are included for comparison (black squares), which overlap in composition with the plagioclase in our samples.

also always present but vary in strength among intrusive samples. The only extrusive rocks that display a detectable $\sim 1.25 \mu\text{m}$ absorption are plagioclase-phyric basalts and one glass-rich silicic dome rock. All other extrusive rocks do not have a clear $1.25 \mu\text{m}$ absorption (Figure S18 in Supporting Information S1), show spectral variability between the same rock type, and spectral similarity between dramatically different rock types (e.g., basalt, rhyolite, and ignimbrite).

The 19 rocks with potential $1.25 \mu\text{m}$ plagioclase absorption band fall into four spectral groups based on similarities in absorption features and spectral slope (Figure 4). An overview of the characteristics of these groups can be found in Table 5. The groups were created agnostic of rock type to assess whether or not samples can be grouped petrologically based on spectral similarities. The 23 rocks that have no plagioclase-like absorption are shown in Figure S18 in Supporting Information S1 and not discussed in the main text. In the following, we refer to mineral-dominated spectral groups, such as “plagioclase-dominated spectral group.” Here, we mean that the spectra of the rocks in a given group are dominated by that mineral, not necessarily that the rock lithology is dominated by that mineral.

4.2.1.1. Plagioclase-Dominated Spectral Group

Rocks in this group have strong $1.25 \mu\text{m}$ bands and neutral or slight blue-slope, and the $1.25 \mu\text{m}$ absorptions strongly resemble plagioclase absorption (Figures 2a and 4a, group G1). This group is made up of one monzonite, five granodiorites, and one granite-granodiorite, and is most similar to Fe-bearing plagioclase spectra because of the distinct and symmetrical $1.25 \mu\text{m}$ band, and lacks the steep red-slope and strong $>2 \mu\text{m}$ bands common in hydrous mafic minerals (Figure 2b). Despite this group containing 9.3–22.8 vol.% hydrous mafic minerals, these rocks still appear to exhibit a detectable plagioclase absorption.

4.2.1.2. Hydrous Mafic-Dominated Spectral Group

This group has spectra dominated by a very steep red-slope between 1.1 and $1.8 \mu\text{m}$ (Figure 4a, group G2), complex narrow bands from 2.2 to $2.4 \mu\text{m}$ that are much stronger than any other samples, and a broad absorption band centered near $1.15 \mu\text{m}$. This group, consisting of three tonalites, appears spectrally dominated by hydrated

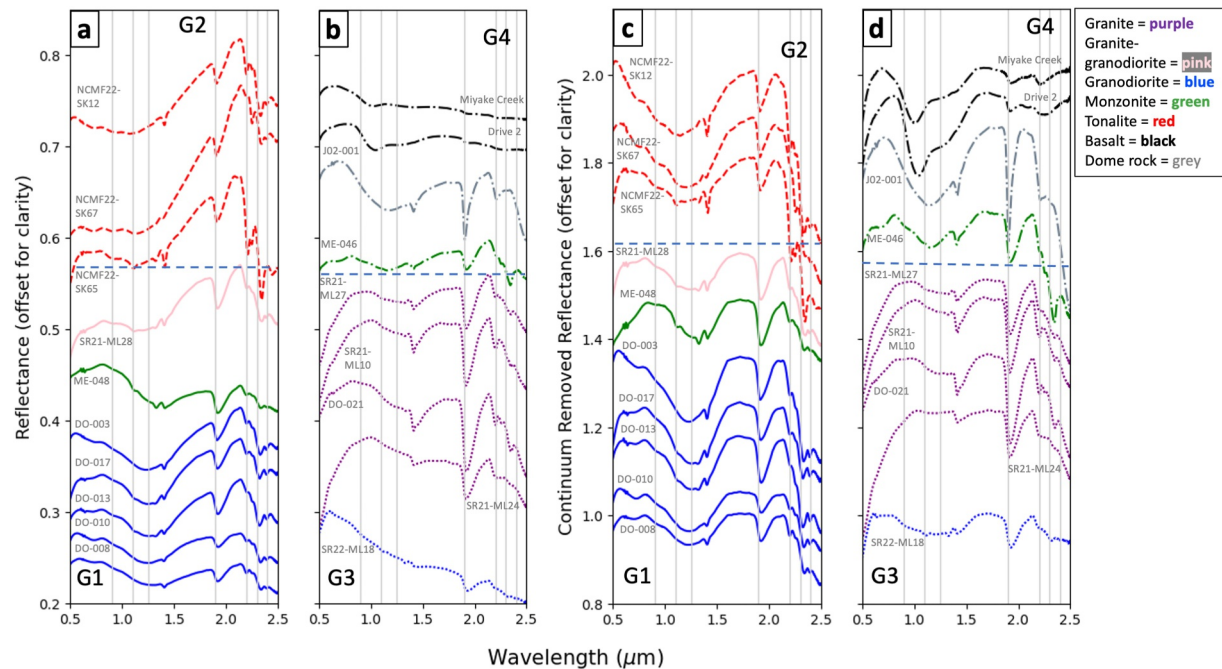


Figure 4. Whole-rock spectra of 19 igneous samples with possible 1.25 μm bands organized based on spectral grouping. These include granites (purple), granite-granodiorite (pink), granodiorites (blue), monzonites (green), tonalites (red), basalts (black), and a glassy dome rock (gray). (a) G1 indicates the plagioclase-dominated spectral group with strong 1.25 μm absorption and weak $>2 \mu\text{m}$ bands (bottom; solid lines) and G2 indicates the hydrous mafic mineral-dominated spectral group with strong red-slope and $>2 \mu\text{m}$ bands (top; dashed lines), separated by a blue horizontal dashed line. (b) G3 indicates the weak absorption spectral group with weak 1.25 μm band absorption (bottom; dotted lines) and G4 indicates the ambiguous spectral group with 1.25 μm bands similar but not confidently attributable to plagioclase absorption (top; dot-dash lines), also separated by a horizontal dashed line. Panels (c, d) same as (a) and (b) but with continuum removed spectra.

mafic minerals (Figure 2b), despite containing a similar plagioclase abundance to the plagioclase-dominated spectral group. The abundance of mafic minerals in this group ranges from 6.9 to 11.3 vol.%, implying the mafic minerals exert a disproportionate control over the bulk spectra, in contrast with the previous group.

4.2.1.3. Weak Absorption Spectral Group

This group is characterized by a steep red-slope below 0.9 μm , a neutral or blue spectral slope from 0.9 to 2.5 μm , a weak 1.25 μm band, and weak or absent $>2 \mu\text{m}$ absorptions (Figure 4b, group G3). Though the plagioclase abundance is similar to that of the plagioclase-dominated group, this group exhibits a weak or absent 1.25 μm feature. The 1.4 and 1.9 μm bands tend to be the strongest of the spectral groups. This group is composed of one granodiorite, one aplite, and three granites. The lack of distinct spectral features, steep short wavelength red-slope, and overall blue-slope resembles spectra dominated by spectrally neutral felsic minerals (Figure 2a). The blue-slope is consistent with highly reflective materials that scatter more light at shorter wavelengths, common in feldspathic or felsic rocks (Clark, 2004; Hapke, 1993; Hunt & Salisbury, 1970).

4.2.1.4. Ambiguous Spectral Group

This group has samples whose spectra either did not fit into a group or are ambiguous plagioclase detections (Figure 4b, group G4), in that they share traits with spectrally feldspathic detections, but deviate from the typical 1.25 μm absorption attributed to plagioclase. These include one monzonite, one glassy high-silica dome rock, and two plagioclase-phyric basalts. The monzonite has similar spectral features to the plagioclase-dominated group, except it has an ambiguous 1.25 μm absorption because the band is shallow and shifted to $\sim 1.15 \mu\text{m}$. The basalts and glassy dome rock are spectrally and lithologically distinct from one another, but still have absorption that overlaps with the plagioclase 1.25 μm band. The dome rock exhibits a broad absorption centered around 1.15 μm that appears similar in shape to a plagioclase band but is shifted to a lower wavelength i.e. closer to the band position of iron-bearing glass (e.g., B. H. N. Horgan et al., 2014). The two plagioclase-phyric basalts exhibit strong ~ 1.03 and $1.05 \mu\text{m}$ absorptions consistent with clinopyroxene and are thus quite distinct from the other

rocks, but the shallow absorption near 1.25 μm aligns with the typical plagioclase band. However, olivine absorption bands can also cause a broad shoulder in a similar region, leading to ambiguity.

4.2.2. Spectral Properties by Rock Type

Band parameter plots derived from VNIR whole-rock spectra (Figures 5b–5d) reveal some systematic differences that can differentiate lithology, although there is some overlap between rock types. The samples in the plagioclase-dominated spectral group cluster due to their similar 1.25 μm band position, neutral slope, and fairly weak >2 μm absorption bands, and are primarily granodiorites. In contrast, the hydrous mafic-mineral dominated spectral group, composed of tonalites, has a high SWIR slope (>0.1), a lower wavelength band center (<1.2 μm ; Figure 5c), and strong >2 μm band depth (Figure 5d). Under visual inspection, the whole-rock spectrum of granite-granodiorite SR21-ML28 looks like a hybrid of the plagioclase- and mafic-dominated spectral groups, exhibiting both a fairly strong red-slope and 1.25 μm band center (Figure 4, pink spectrum). However, band parameter space (Figures 5b–5d, orange triangle) shows that its 1.25 μm band, slope, and >2 μm absorptions are a close match to the plagioclase-dominated spectral group, and significantly offset from the mafic-dominated tonalites. Thus, mafic-mineral dominated tonalites can be distinguished from plagioclase-dominated granodiorites and monzonites based on whole-rock spectra observation and band parameter analyses (Figures 4 and 5b–5d). These are distinct from more spectrally neutral granites. Some granitic rocks (weak absorption spectral group) and plagioclase-phyric basalts (ambiguous spectral group) have minimal >2 μm bands and similar spectral slope (Figures 5b–5d), but they are clearly distinguishable based on the strong 1 μm absorption band in the basalts (Figure 4c).

Figure 6 compares the 1.25 μm band depth parameter to plagioclase iron content and modal abundance. We find no clear correlation between whole-rock band depth and iron content, especially among felsic rocks, but do find a positive correlation between band depth and plagioclase vol.%. No rocks containing plagioclase with <0.13 wt.% FeO or plagioclase abundance $<\sim 3$ vol.% showed clear 1.25 μm absorption, though these limits may be affected by the alteration state of the rock (discussed in Section 5.2.2).

4.2.3. VNIR Spectral Scans

To identify specific mineral phases and better understand how they contribute to the bulk whole-rock spectra and to identify the presence of minerals, we analyzed high-resolution SWIR spectra of individual minerals within the 19 samples comprising the different spectral groups, and then compared their spectral characteristics using band parameter analyses. Example component spectra, spectral parameter images, and sample images in natural color from four spectral groups are shown in Figure 7. Natural color images, spectral parameter maps, and all extracted spectra for each sample can be found in Supporting Information S1. Below we discuss the scan results for each spectral group.

4.2.3.1. Plagioclase-Dominated Spectral Group

As shown in Figures 7a–7c, strong 1.25 μm absorptions are associated with coarse plagioclase grains and are abundant across the sample surface in the PM spectral maps (red areas, Figure 7c; Figures S8–11, S13 in Supporting Information S1) and are a match to library plagioclase spectra (Figure 2). Hydrous mafic minerals are also clearly identifiable in the maps (yellow/green areas, Figure 7c). Blue or dark-colored regions coincide with more spectrally neutral felsic mineral grain clusters or individual felsic mineral grains.

Spectra of individual plagioclase grains in these samples strongly resemble the whole-rock spectra, including clear 1.25 μm iron bands that align with the 1.25 μm whole-rock band centers. Weak >2 μm features are also present in the plagioclase grain spectra at 2, 2.5, and 2.35 μm likely due to contamination by mica or secondary clay minerals, but their contributions are minimal. K-feldspar and quartz are indistinguishable from one another in the VNIR scans, are spectrally neutral, and therefore not responsible for the strong 1.25 μm absorption (Figure 7; orange spectrum). Taken together, these observations indicate that coarse plagioclase feldspar grains are the primary contributors to the whole-rock 1.25 μm band despite hydrous mafic mineral abundances between 9.3 and 22.8 vol.% for samples in this group.

Hydrous mafic minerals were clearly distinguishable from other minerals in the VNIR scans based on their low albedo, strong red spectral slope with a broad band centered near 1.2 μm , and strong >2 μm bands (Figure 7a). Amphibole was identified via its two narrow bands at ~ 2.32 and ~ 2.4 and 2.3 μm shoulder (Figure 2). Mineral

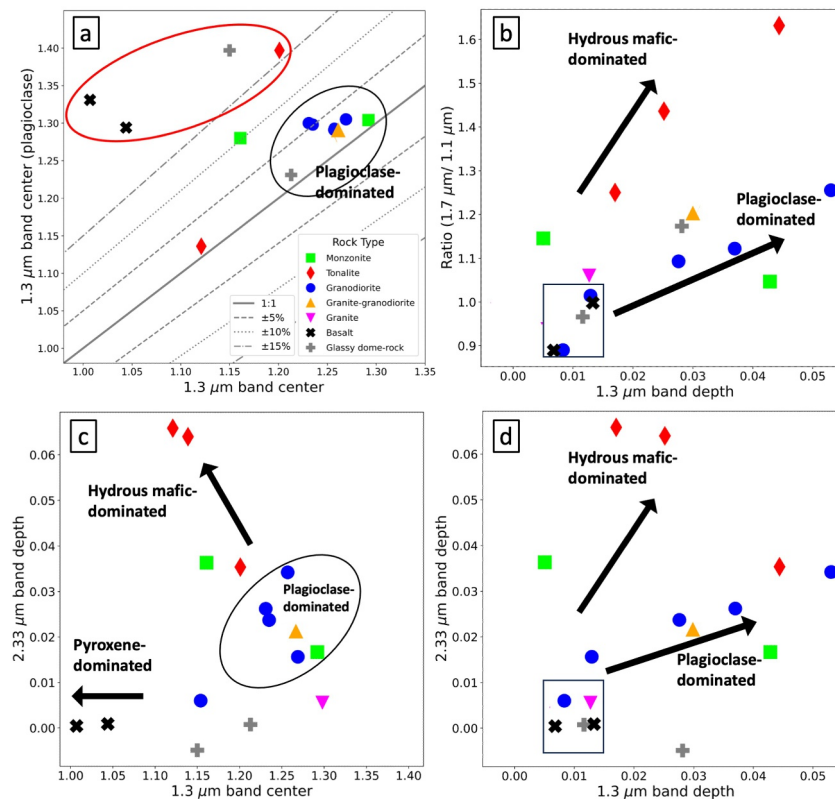


Figure 5. Band parameter plots derived from whole-rock and individual plagioclase grain spectra, where rock types are differentiated by color as in Figure 4. (a) Comparison of the 1.3 μm band center of individual plagioclase grains versus their host whole rock. Group 1 rocks tend to plot close to the 1:1 line in a cluster (black circle), implying plagioclase dominates the whole-rock spectrum. Outliers tend to cluster above the line (red circle). (b) Comparison of 1.3 μm band depth to the 1.7/1.1 μm ratio, where high ratio indicates stronger red-slope. Tonalites (spectrally hydrous mafic mineral-dominated) plot at high red-slope and lower band center, and granodiorites (spectrally plagioclase-dominated) group at higher band center and more neutral slope. The black square denotes rocks that are more ambiguous in this parameter space and vary in rock type. (c) Comparison of 1.3 μm band center to 2.33 μm band depth. Tonalites tend to plot at high 2.33 μm band depth and low band centers, and basalts are defined by band centers closer to 1 μm . Plagioclase-dominated rocks cluster together (black circle). (d) Comparison of 1.3 μm band depth to 2.33 μm integrated band depth, which yields a similar trend as (b).

spectra with weak absorptions at 2.25, $\sim$ 2.32, and 2.4 μm are a match to library spectra of chlorite or a combination of chlorite and biotite (Figure 2). These minerals likely contribute to four narrow bands of weak to moderate strength at 2.2, 2.25, $\sim$ 2.32, and 2.4 μm observed in the whole-rock spectra, and are consistent with complex OH band combinations (J. Bishop et al., 2002; J. L. Bishop et al., 2008; Clark et al., 1990; Hunt & Ashley, 1979; Hunt & Salisbury, 1970; King & Clark, 1989; Mustard, 1992). For each rock in this spectral group, amphibole, biotite, and minor chlorite (typically <2.5 vol.%) were detected with XRD. Though the strength of the >2 μm hydrous mineral absorptions and overall red-slope are clear in individual mineral spectra, they are much weaker contributors to the whole-rock spectra of this group.

4.2.3.2. Hydrous Mafic Mineral-Dominated Group

As shown in Figures 7d–7f, the whole-rock spectra in this group are most similar to spectra from individual grains of hydrous mafic minerals, despite the three tonalites comprising this group being felsic in modal composition (>80 vol.% felsic minerals) and containing <12 vol.% hydrated mafic minerals. PM spectral parameter images (Figure 7f, Figures S5 and S6 in Supporting Information S1) tend to be more homogeneous in color than the plagioclase-dominated spectral group. Red and cyan colors are associated with hydrous mafic minerals, and green/dark colors are associated with quartz and alkali feldspars. Other than hydrous mafic minerals, the vast majority of felsic minerals within these samples are weak absorbers and thus express little variability in band parameter values. In Figure 7f, red colors that normally correspond to 1.25 μm absorption strength are associated with mafic mineral absorption because there are no strong absorptions by plagioclase grains, in contrast with the plagioclase-dominated spectral group scan (Figure 7c).

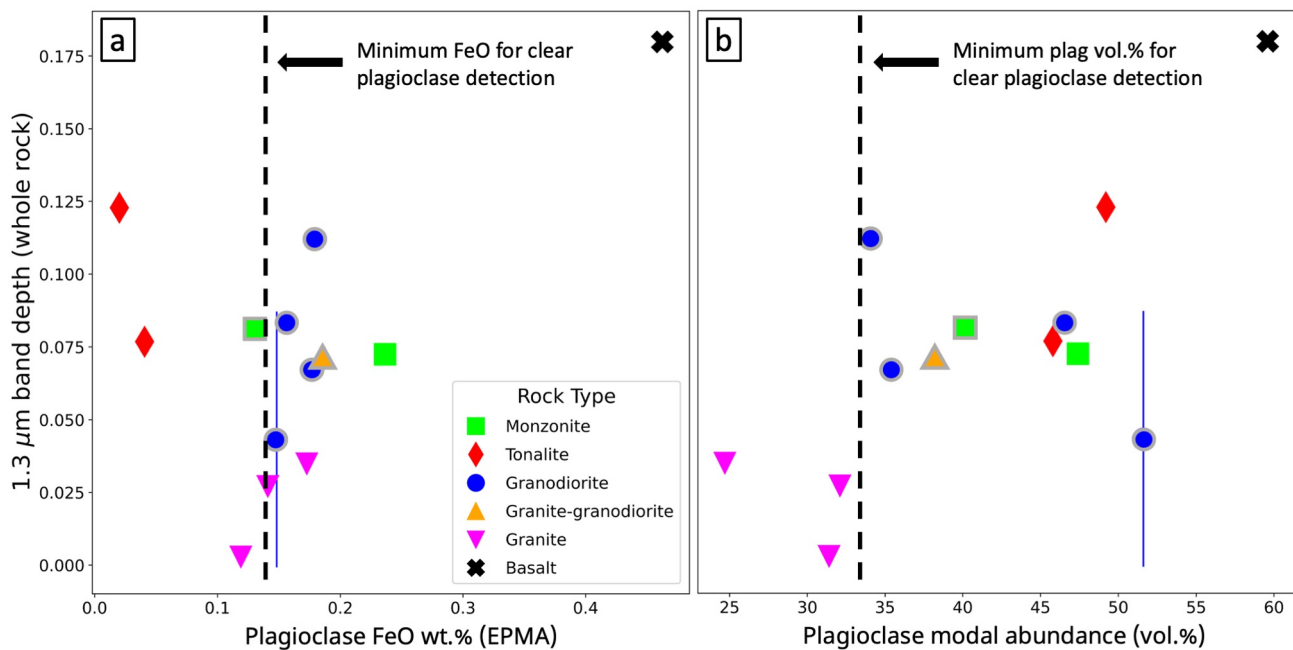


Figure 6. Chemical data versus whole-rock 1.3 μm band depth. Symbols with a gray border are part of the plagioclase-dominated spectral group. (a) EPMA derived plagioclase FeO content (wt.%) versus whole-rock 1.3 μm band depth. (b) XRD derived plagioclase weight percent versus whole-rock 1.3 μm band depth. There is no clear trend between plagioclase iron content and whole-rock 1.3 μm band depth, and there is a roughly linear positive correlation between plagioclase vol.% and whole-rock 1.3 μm band depth. The black dashed lines indicate the minimum quantity of FeO in plagioclase (a) and plagioclase abundance (b) required for a plagioclase absorption to appear in the bulk spectrum of rocks in this study, and both must be exceeded. For instance, the tonalites (red diamonds) exceed the required plagioclase content but lack sufficient iron in the plagioclase. However, even exceeding both dashed lines does not guarantee a plagioclase absorption.

The strong red slope and narrow 2.25, 2.33, and 2.4 μm absorptions are consistent with a combination of biotite and chlorite Mg- and Fe-OH bands (Figure 2). These minerals were also detected in the XRD data (Figures 2 and 7d, Figures S5 and S6 in Supporting Information S1). In one sample (NCMF22-SK65), we observe minerals with relatively flat spectra and absorption at 2.2, 2.35, and 2.45 μm, more consistent with muscovite, and XRD data confirms that this is the only sample with muscovite. NCMF22-SK65 also shows abundant chlorite-like individual mineral grains (Figure S5 in Supporting Information S1) with a steep red-slope and strong ~2.35 μm absorption, along with a weaker absorption at 2.25 μm (Figure S5 in Supporting Information S1). Despite the difference in phase and abundance of hydrous minerals, and in turn degree of alteration, the overall spectral shape and >2 μm bands of SK65 and SK67 are similar.

Individual plagioclase grains are challenging to identify based on 1.25 μm absorption and are almost always spectrally indistinguishable from light-toned felsic mineral grains (Figure 7d, Figures S5 and S6 in Supporting Information S1). Plagioclase and the felsic minerals (quartz, K-feldspar) all have clear 1.9 μm hydration bands, an asymmetric 1.4 μm band, and are often associated with weak 2.2, 2.25, and ~2.33 μm absorptions. These are a match with OH and H₂O bands exhibited by a combined muscovite and chlorite spectrum (Figure 2). Together, they support a mixed mica–chlorite alteration assemblage rather than a single hydrous phase. However, we infer that the depletion in iron in plagioclase, rather than the association with secondary hydrated minerals, is driving the lack of plagioclase absorption; the plagioclase-dominated spectral group has a similar or greater abundance of hydrous minerals, but no iron depletion, and still exhibits strong 1.25 μm bands.

4.2.3.3. Weak Absorption Spectral Group

As shown in Figures 7g–7i, spectrally neutral grains are clearly the most areally dominant minerals, differing from other spectral groups where a more even mix of minerals is observed. The PM band parameter images (Figure 7i, Figures S12, S14–S17 in Supporting Information S1) are dominated by dark green or black colors associated with spectrally neutral minerals, and infrequent bright green and red colors associated with hydrous mafic minerals and plagioclase absorptions respectively. The blue-sloped and relatively spectrally bland whole-

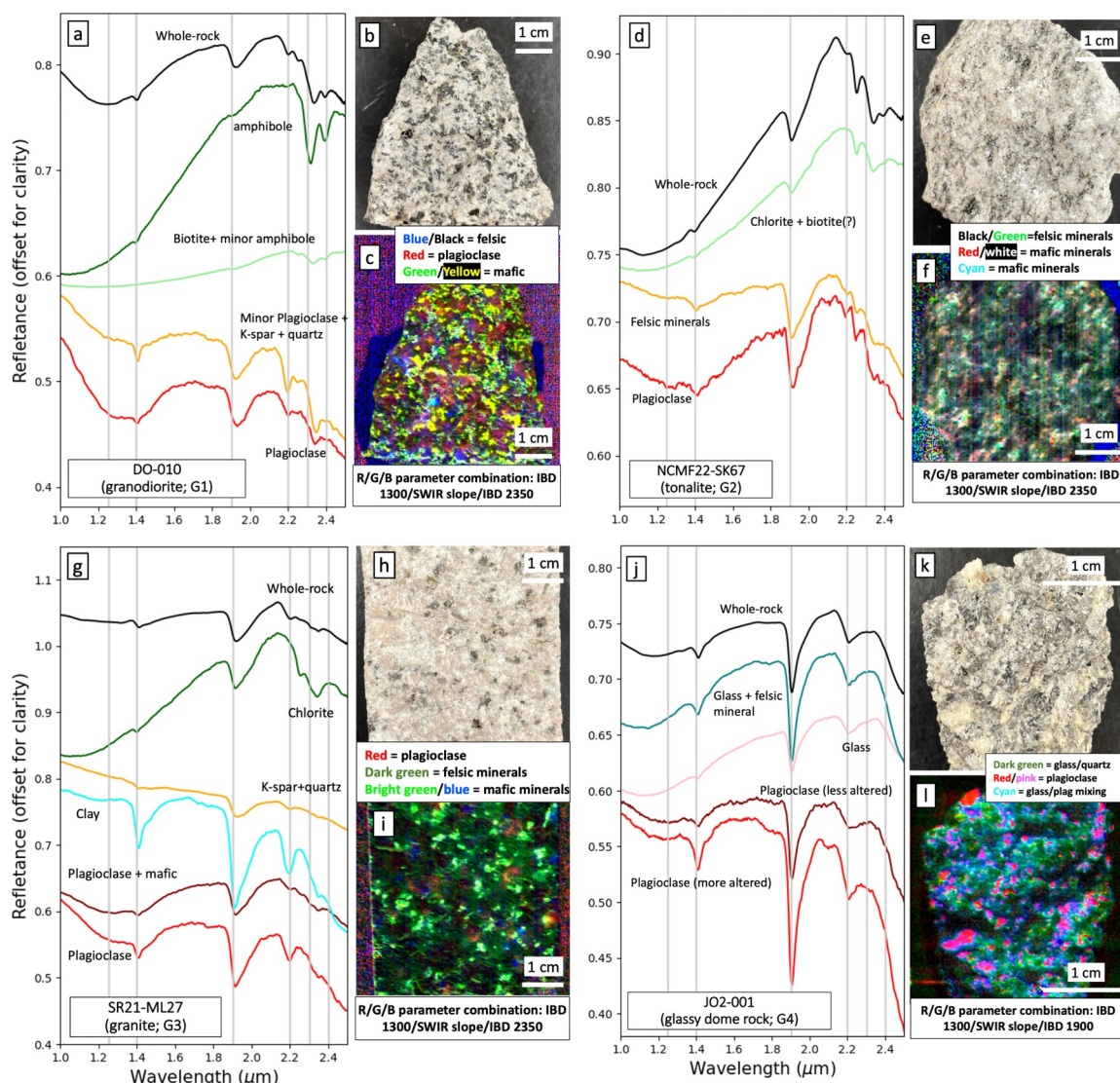


Figure 7. Mineral spectra and mineralogical maps derived from high-resolution visible to near infrared scans of representative samples from each main spectral group. Legends indicate which colors correspond to mineral type. RGB color composites correspond to red: IBD 1300, green: SWIR slope, blue: IBD 2350, except as noted for the final image. (a) Representative spectra from granodiorite DO-010, part of the plagioclase-dominated spectral group. (b) Natural color image of DO-010. (c) Spectral parameter image displayed in RGB to emphasize plagioclase and hydrous-mafic minerals. Red indicates plagioclase, green/yellow indicates mafic minerals, and black or dark colors indicate Fe-poor minerals (e.g., K-feldspar, quartz). Panels (d–f) same as (a–c) but for tonalite NCMF22-SK67 of the hydrated mafic-dominated spectral group. Here cyan and red/white correspond to different hydrated mafic minerals. Panels (g–i) same as (a–c) but for granite SR21-ML27 of the weak absorption group. Panels (j, k) same as (a, b) but for glassy dome rock JO2-001 from the ambiguous spectral group. No hydrated mafic minerals were observed in this sample, so we changed the RGB combination to red: IBD 1300, green: SWIR slope, blue: IBD 1900. Dark green corresponds to glass/quartz, red/pink to plagioclase, and cyan corresponds to glass/plagioclase mixing and is found at plagioclase grain rims.

rock spectra of this sample group are most similar to the spectral characteristics of felsic minerals K-feldspar and quartz grains, consistent with the parameter images.

Plagioclase is rarely detected in the spectral scans even though XRD data indicates a similar abundance to the plagioclase-dominated spectral group. Individual plagioclase grains were rarely identifiable based on a strong 1.25 μm absorption, but the bands were still occasionally observed in most of the samples (Figure 7i, red spectrum). The bulk spectra in turn express weak or absent 1.25 μm plagioclase bands.

Hydrous mafic mineral detections are sparse compared to previous spectral groups, which is consistent with the <5 vol.% hydrous minerals detected with XRD. They are associated with a strong red-slope, and commonly display a strong 1.9 and 2.35 μm absorption, and a weak 2.25 μm absorption consistent with a chlorite-dominated

spectrum (Figure 7g, green spectrum). This is clearest in sample DO-021 (Figure S16 in Supporting Information S1), where bright cyan veins in the RGB maps are associated with chlorite, a clear sign of hydrothermal alteration. In addition, samples throughout this group exhibited areas with spectra exhibiting sharp 1.4, 1.9, and 2.2 μm absorptions (Figure 7g, cyan spectrum) consistent with an Al-OH-bearing alteration phase such as montmorillonite (Figure 2), derived from an initial stage of feldspar alteration (Hunt et al., 1973), though this phase is not widespread across the sample surfaces.

The reduced plagioclase band strength is most likely due to multiple obscuring factors reducing spectral contrast (discussed further in Section 5.2), but alteration of plagioclase grains seems to be the most important factor for this group. The presence of Al-clays is the only common factor among these samples, which otherwise have similar plagioclase abundances and iron contents as the plagioclase-dominated spectral group. In three of the five samples of this group (SR21-ML27, SR21-ML10, DO-021), there is a weak 1.25 μm absorption in the whole-rock spectrum consistent with plagioclase absorption, overprinted with a narrow 1.4 μm absorption from montmorillonite. Despite the sparse presence of plagioclase absorption features across the sample surfaces, the $\sim 1.25\text{-}\mu\text{m}$ band that we attribute to plagioclase still influences the whole-rock spectra (Figure 7g), likely possible due to the lack of hydrous mafic mineral absorptions detected in spectral scans.

4.2.3.4. Spectrally Ambiguous Group

The monzonite (ME-046; Figure S7 in Supporting Information S1) is in this group due to a weak 1.25 μm band shifted to shorter wavelengths ($\sim 1.15\text{ }\mu\text{m}$) and a neutral spectral slope. We suspect the alteration is a major cause of the difference between this sample and the monzonite (ME-048) in the plagioclase-dominated spectral group, which has a clearer 1.25 μm absorption and lacks strong $>2\text{ }\mu\text{m}$ bands. The strongest absorption band among the individual minerals in sample ME-046 occurs at $\sim 2.33\text{ }\mu\text{m}$, consistent with chlorite. Other than the tonalites in the hydrous mafic mineral-dominated group, this sample's whole-rock spectrum shows the strongest 2.33–2.35 μm absorption of any sample. The sample also shows a clear hydrothermal alteration band running through part of the rock. Plagioclase grains have a weak 1.25 μm band and the mafic mineral grains tend to lack a strong red-slope, likely due to alteration, which explains the neutral spectral slope and 1.25 μm band ambiguity in the whole-rock spectrum.

For the glass-rich dome rock (JO2-001), the PMH band parameter image (Figure 7i) shows 1.25 μm absorption associated with plagioclase grains. Glassy material is abundant and associated with a dark green color in the band parameter images, and appears both dark and light toned in the natural color image (Figure 7k). The glass is associated with a broad band centered closer to $\sim 1.15\text{ }\mu\text{m}$, consistent with absorption bands in iron-bearing glass (Cannon et al., 2017; Cloutis et al., 1990a; B. H. N. Horgan et al., 2014). In natural color, it is challenging to distinguish the more plagioclase-like minerals from light-toned glassy material. We find that plagioclase grains are spectrally dominant over glassy material despite being at lower abundances throughout the sample. We extracted spectra from glassy portions and white mineral grains and found band centers at ~ 1.15 and $\sim 1.25\text{ }\mu\text{m}$ respectively (Figure 7j, Figure S4 in Supporting Information S1); the latter is a closer match to the whole-rock spectrum. A different glass-rich dome rock (JO2-002; Figure S4 in Supporting Information S1) has a much higher proportion of dark silicic glass, and its plagioclase grains have a much weaker 1.25 μm absorption band (Figure 7j, Figure S5 in Supporting Information S1). The whole-rock spectrum of the more glass-rich sample is flat, with no discernible absorption features other than minor 1.9 and 2.2 μm absorptions. Despite coming from the same eruption, they exhibit dramatically different bulk spectra due to differing glass and phenocryst abundance.

The whole-rock spectra of the two plagioclase-phyric basalts exhibit a strong 1 μm absorption from pyroxene (Figure 8a), despite the confident detection of few pyroxene phenocrysts in band parameter images (only five in sample Drive-2). The groundmass itself only exhibits a weak 1 μm absorption distinct from the strongly absorbing individual mineral grains (Figures S1 and S2 in Supporting Information S1). Infrequent olivine phenocrysts ($<1\text{ mm}$) were observed, but the absence of a shoulder on the short-wavelength side of the 1 μm band in the bulk spectrum implies olivine does not contribute significantly to this feature. This is supported by XRD data which yielded a 5.3 vol.% olivine abundance. In areas of the rock surface containing plagioclase phenocrysts with no accompanying pyroxene or olivine, the spectrum shows a 1.25 μm band more clearly attributable to plagioclase. For example, spectra from a region on sample Drive 2 with equal parts plagioclase and groundmass show a strong 1.25 μm band similar to spectra from individual plagioclase grains, though a weak 1 μm band from the groundmass remains (Figure 8, blue dash-dot line). These results indicate that a clear plagioclase band may be

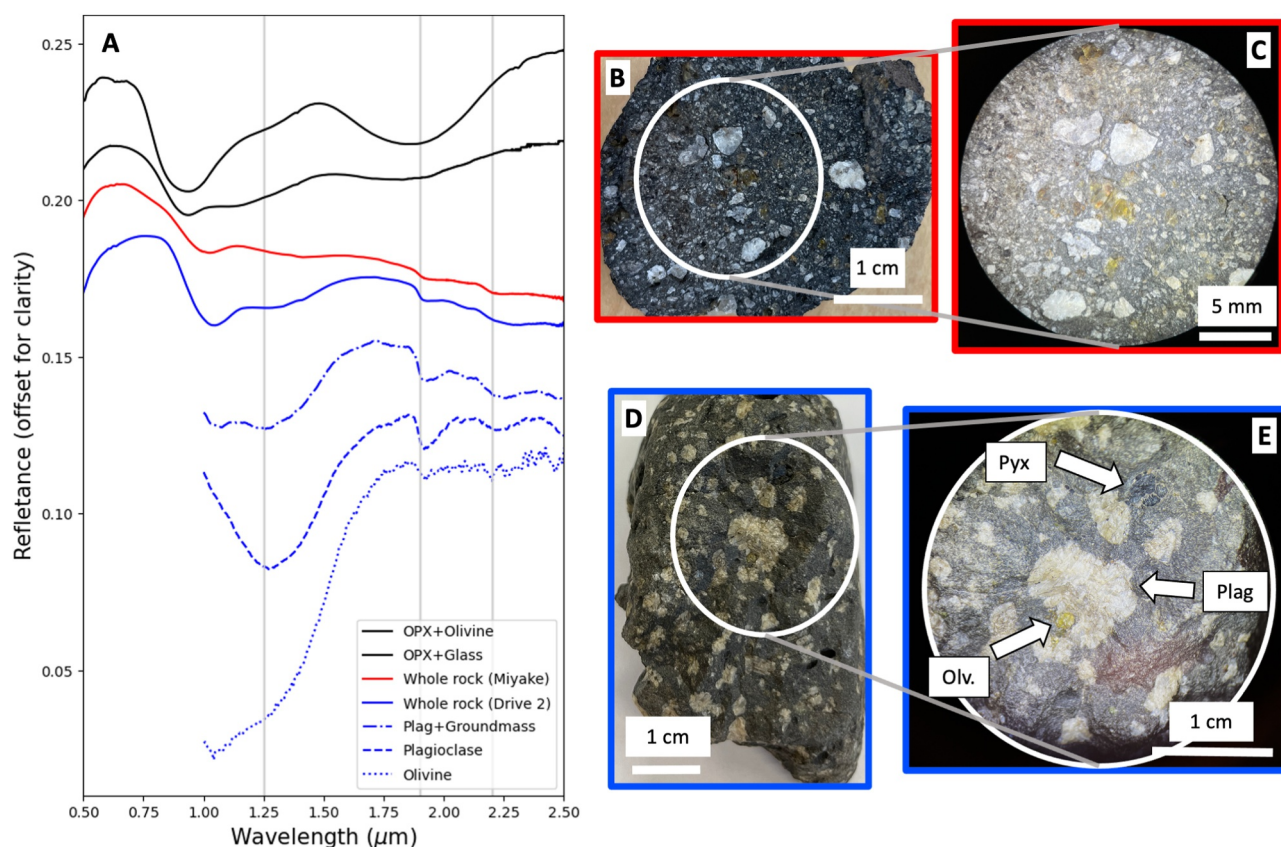


Figure 8. Spectra and sample photos from plagioclase-phyric basalts. (a) Solid black lines are OPX + olivine and OPX + glass laboratory mixtures (B. H. N. Horgan et al., 2014), and the colored spectra correspond to the sample image borders with matching color. Solid red and blue lines are whole-rock spectra. The blue dotted, dashed, and dot-dash lines show average spectra from olivine, plagioclase, and plagioclase + groundmass spectra from the same rock as the solid blue line. (b, c) Sample Miyake Creek and (d, e) Sample Drive 2. Both are plagioclase-phyric but have accompanying olivine and pyroxene phenocrysts that contribute to the 1 and 1.25 μm absorption. In these cases, the 1.25–1.3 μm absorption in the whole-rock spectra is not confidently attributable to plagioclase and appears similar to the mixture spectra of significantly different composition.

detectable in a plagioclase-phyric basalt only if the pyroxene is confined to the groundmass, because a small number of pyroxene phenocrysts can effectively mask the plagioclase signature or produce spectra very similar to mineral mixtures with substantially different mineral abundances (Figure 8, panel (a), black lines; see Section 5.2.1 for further discussion).

4.2.4. Scanned Sample Band Parameters

We have qualitatively compared band positions and shapes of minerals in whole-rock spectra to evaluate which minerals are dominant. Here we expand on this with band parameter analyses, which provide a more precise comparison of absorption band positions between plagioclase and the host whole-rock spectra.

Band centers from individual plagioclase grain spectra are almost an exact match to many of the band centers from the bulk spectra of the host rocks, providing further evidence that plagioclase is a primary influence on the 1.25 μm band of granodiorites and one monzonite. Figure 5a shows a plot of individual plagioclase mineral band center versus whole-rock band center; all granodiorites, one granite-granodiorite, one monzonite, and one glassy dome rock cluster together within $\sim 5\%$ deviation from the 1:1 line. Five of these rocks are from the plagioclase-dominated spectral group and one from the ambiguous group, which we infer to exhibit a 1.25 μm band dominated by plagioclase in their bulk spectra. These comparisons were limited to samples with whole-rock spectra displaying a clear 1.25 μm detection and a band depth >0.02 , which excluded the weak absorption spectral group. The spectrally ambiguous group was included because they exhibit a shallow absorption that may be caused by plagioclase at ~ 1.25 , and were less subject to the 1.4 μm absorption that complicated interpretation of the 1.25 μm band in the weak absorption spectral group.

We assert that rocks plotting outside of 10% deviation from the 1:1 line are strongly influenced by mafic minerals. One tonalite, two basalts, and a glassy dome rock (with minimal plagioclase grains compared to the other dome rock) cluster above the 15% deviation line because their plagioclase grains have a much higher $\sim 1.25\ \mu\text{m}$ band center than the dominant band center in the bulk whole-rock. Though one tonalite plots near the 1:1 line, it has a $\sim 1.12\ \mu\text{m}$ band center, well below the typical $1.25\ \mu\text{m}$ plagioclase absorption. Because the plagioclase absorption is extremely weak in this sample, spectra extracted from plagioclase grains are likely contaminated by adjacent mafic minerals. As a result, the near 1:1 correspondence reflects a similarity between the whole-rock band center and mafic mineral band center rather than a plagioclase-derived absorption. All of these samples are in the mafic-dominated or ambiguous spectral group.

4.3. TIR Spectra

TIR models tend to overestimate plagioclase in our samples, and hydrous mafic minerals are not detected in intrusive samples. Of 12 samples with both TIR and XRD, 11 model results are within 20 vol.% of the plagioclase XRD measurements and 7 are within 15% accuracy (Figure 9). The model results are consistently within 20 vol.% for quartz. For coarse-grained felsic intrusive rocks, the model tends to consistently overestimate plagioclase abundance and underestimate K-feldspar or not model it at all. Hydrous minerals occur at abundances lower than 15 vol.% and are not detected and thus not included in the models. Tonalites, which are composed of <10 vol.% K-feldspar and have abundant plagioclase and quartz, were the best modeled samples of all intrusive rocks.

Plagioclase-bearing coarse-grained felsic rocks are distinct from basalts and anorthosites at THEMIS resolution (e.g., Phillips et al., 2022; Rogers et al., 2005; Rogers & Nekvasil, 2015), which is also true in our study, but the felsic rocks in our sample suite are generally not distinct from one another (Figure 10). The laboratory TIR spectra, convolved to THEMIS bands, exhibit emissivity minima that range from 8.82 to $9.34\ \mu\text{m}$ for the same 12 rocks considered above. The basalt is the clear outlier at $9.34\ \mu\text{m}$, consistent with its significantly lower silica content. The rest of the rocks are felsic and fall between 8.82 and $9.03\ \mu\text{m}$. Ten of the rocks fall between the narrow range of 8.82 and $8.89\ \mu\text{m}$ despite varying in silica content as much as 15 wt.%, implying that the spline fit minima parameter is not a precise indicator of silica content for the felsic rocks in our sample set. The basalt minimum is low compared to other studies (Rogers & Nekvasil, 2015), which may be due to low spectral contrast in our sample and a jump in emissivity near $10.21\ \mu\text{m}$, which shifted the band minimum to shorter wavelengths.

5. Discussion

5.1. Connecting VNIR Spectral Properties to Lithologic Groups

Certain felsic intrusive rock types, particularly granodiorites and tonalites, exhibit characteristic absorption features and spectral slopes that distinguish them from other lithologies' whole-rock spectra (Figure 5). Tonalites are parameterized by a steep spectral red-slope, a broader $1.25\ \mu\text{m}$ absorption centered at shorter wavelengths, and a high $2.33\ \mu\text{m}$ band depth (Figure 5d), each of which we attribute to mafic hydrous minerals, such as amphibole. Granodiorites have absorption band centers (1.25 – $1.35\ \mu\text{m}$) and slopes (0.00 – 0.07) that we attribute to plagioclase feldspar. They also tend to have low $>2\ \mu\text{m}$ band depth and a neutral spectral slope, implying they are less influenced by amphibole, chlorite, or secondary clays compared to tonalite. Among our sample set, granodiorites showed the strongest $1.25\ \mu\text{m}$ plagioclase band depth, and overall tend to have higher $1.25\ \mu\text{m}$ band depth compared to other lithologies. We found granites were the least distinguishable lithology due to their lack of absorption features, though they consistently have flat or blue spectral slopes (Figure 4). The band parameter space we used is ineffective for comparing the basalts, glassy dome rock, and granites because they overlap with one another. However, the strong absorption at or just above $1\ \mu\text{m}$ in the dome rock and basalts clearly distinguish them from the granites, and in turn would be clearly distinguishable from orbit.

Some potential ambiguities in determining rock type via VNIR plagioclase detection can be ameliorated with TIR data. For instance, if the $1.25\ \mu\text{m}$ bands of an anorthosite or plagioclase-phyric basalt and granodiorite look similar, the primary MIR spectral band center of the granodiorite ranges from 9.0 to $9.2\ \mu\text{m}$, distinct from typical basalt/anorthosite band centers $>10\ \mu\text{m}$ (e.g., Christensen et al., 2004; Rogers & Nekvasil, 2015) and resolvable at THEMIS resolution (Figure 10). However, distinguishing between granite, granodiorite, and monzonite is unlikely due to their similarity at THEMIS resolution (Figure 10).

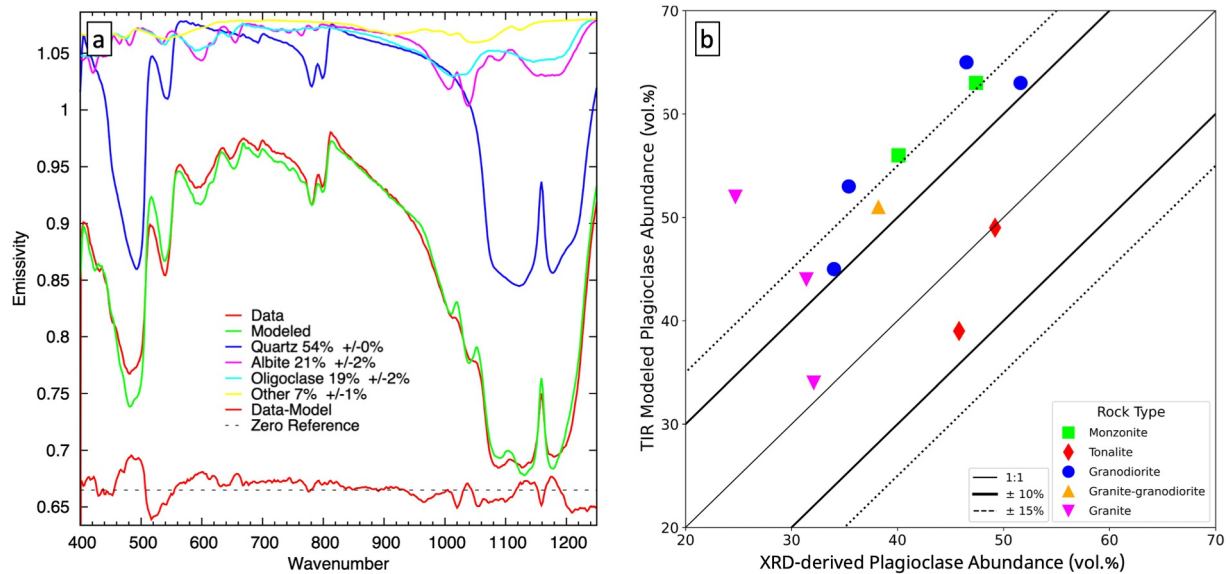


Figure 9. (a) Example TIR deconvolution and calculated mineral abundances for a granodiorite. The red and green overlapping lines show the data and fit respectively, and the other colored lines show the minerals that provide the best fit for the linear deconvolution. (b) TIR deconvolved mineral vol.% versus mineral vol.% (calculated from XRD wt.%) for plagioclase feldspar for 12 samples. TIR models tended to overestimate plagioclase feldspar, especially in granodiorites.

5.2. VNIR Plagioclase Detection: Limits and Influences

For certain rocks, a diagnostic Fe-plagioclase band is clearly detectable in VNIR spectra at lower abundances than the ~85 vol.% previously proposed (Carli et al., 2014; Cheek & Pieters, 2014; Serventi & Carli, 2017; Serventi et al., 2013), a result reported by Barthez et al. (2023, 2026). Spectra from five granodiorites, one granite-granodiorite, and one monzonite support this assertion, and these rocks contain between 34.0 and 51.6 vol.%

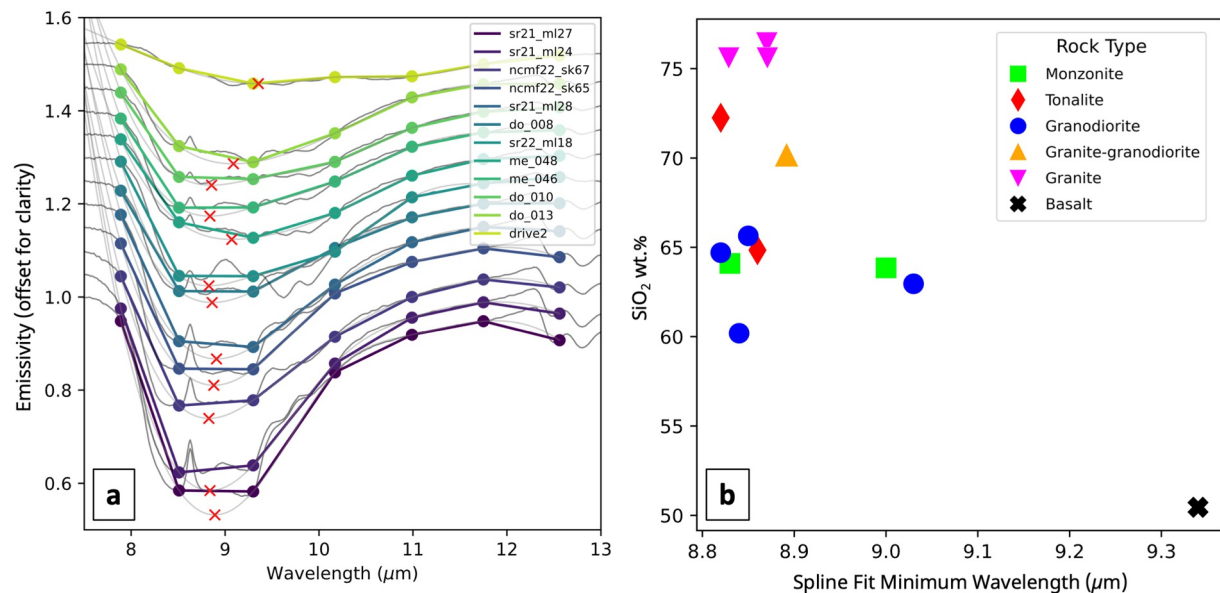


Figure 10. (a) TIR emission spectra convolved with THEMIS bands. The colored lines and points show the THEMIS convolved laboratory data, and the dark gray squiggly lines are the full-resolution laboratory emissivity data. The smooth light gray line is the polynomial fit to the THEMIS convolution, and each red "x" marks the spline fit value. (b) Plot of spline fit band minimum position versus silica content with basalt (black), monzonites (green), tonalites (red), granodiorites (blue), granite-granodiorite (orange) and granites (pink). Other than the basalt, there is significant overlap in spline fit values for the felsic intrusive rocks despite silica content differing up to ~15 wt.%.

plagioclase. These comprise the plagioclase-dominated spectral group, whose key spectral and lithologic information is listed in Table 5, along with the other spectral groups.

We hypothesize that plagioclase grain size and texture, alteration history, and iron content are primary controls on detection, and that intrusive rocks like granodiorites could be detected on Mars from orbit, even with plagioclase abundances below 50 vol.%. Each of these factors can play an important role. For instance, a rock may have sufficient plagioclase abundance to exhibit a diagnostic 1.25 μm absorption, but alteration or depleted plagioclase iron content can inhibit detection, resulting in other mineral phases being spectrally dominant. We also hypothesize it may be possible to detect a strong 1.25 μm plagioclase absorption in plagioclase-phyric basalts, though important caveats must be considered (see following section).

Another key takeaway is that even when mafic hydrous minerals (amphiboles, Fe-bearing clays) are at abundances between 10 and 20 vol.%, they do not seem to obscure the plagioclase absorption in the plagioclase-dominated spectral group (Table 5). Individual hydrous mafic mineral spectra (amphibole, biotite) and secondary alteration phases (chlorite, montmorillonite, muscovite) have a neutral or strong red slope and diagnostic absorption bands between 2.2 and 2.4 μm that are subdued in spectra of these whole rocks, and the plagioclase band can dominate. However, if plagioclase is almost completely depleted in iron, as in our tonalite samples, hydrous mafic minerals dominate the bulk rock spectrum even at 5–10 vol.%.

Quartz and K-feldspar abundance do not seem to have a major influence on the detection of plagioclase. For example, three granodiorites (DO-008, DO-010, DO-013) exhibit a 1.25 μm plagioclase band and have similar band depths, yet K-feldspar + quartz abundance varies from 30 to 52 vol.%. Quartz and K-feldspar do not have strong VNIR absorption bands, so in samples where they are coarse-grained and abundant, we speculate they dilute the spectral contribution of mafic minerals without introducing strong competing absorptions, thereby enabling the presence of the 1.25 μm plagioclase band.

Alteration suppresses the 1.25 μm plagioclase absorption even when plagioclase iron content is sufficient to produce this feature. The weak absorption spectral group has plagioclase FeO contents comparable to the plagioclase-dominated group (Table 5), yet neither whole-rock spectra nor most individual plagioclase grains exhibit a detectable 1.25 μm band. Plagioclase alteration in these samples is indicated by montmorillonite spectra observed in high-resolution scans and chalky plagioclase grains.

In a recent study, Barthez et al. (2026) conducted an investigation of the VNIR spectra of 61 igneous plagioclase-bearing rocks to determine the controls on detection of plagioclase feldspar in VNIR spectra. Our results agree that alteration and the presence of minerals (pyroxene, olivine, Fe-bearing glass) that overlap with the 1.25 μm band can complicate or obscure detection of plagioclase feldspar, and that 1.25 μm band depth and in turn plagioclase detectability increases with plagioclase iron content. However, in contrast to Barthez et al. (2026), we find that the coarse grain size of plutonic rocks strengthens the plagioclase band and is fundamental for its detection in bulk spectra, and that confident detection of plagioclase in bulk spectra of effusive volcanic rocks (particularly basalts) may be more challenging than in coarse-grained plutonic rocks.

5.2.1. Grain Size as a Limiting Factor on Plagioclase Detection

5.2.1.1. Intrusive Rocks

The coarse-grained (>0.75 mm, typically 1–5 mm) nature of our intrusive samples is a critical characteristic for plagioclase detection in whole-rock spectra and reducing the influence of mafic minerals. Among our samples, none of the finer-grained extrusive felsic rocks show any band that could be associated with plagioclase despite some of their coarser-grained intrusive counterparts showing 1.25 μm absorptions. Though some studies have shown increasing grain size can cause absorption band saturation (e.g., Adams & Filice, 1967; Clark et al., 1990; Craig et al., 2008), they focused on mafic minerals which are more subject to those effects because saturation occurs at shorter optical path lengths. For plagioclase, previous studies have shown more coarsely crystalline rocks (Carli et al., 2015) have stronger absorption bands than fine-grained rocks, and that increasing grain size deepens band depth and enables plagioclase to be more detectable in mineral mixtures (Carli et al., 2014; Crown & Pieters, 1987; Pieters, 1983; Serventi & Carli, 2017; Serventi et al., 2013), with which our results agree.

We hypothesize that larger grain size also enables the detection of the 1.25 μm plagioclase absorption despite the presence of primary hydrous mafic minerals (e.g., biotite, amphibole) and secondary minerals (chlorite,

montmorillonite, muscovite), as long as the plagioclase grain itself is not significantly altered. Previous studies establishing plagioclase detection limits relative to mafic mineral abundance (pyroxene, olivine) have shown that the plagioclase 1.25 μm band is strongly subdued if mafic mineral abundance exceeds ~ 15 vol.% (Bell & Mao, 1973; Cheek & Pieters, 2014; Crown & Pieters, 1987; Serventi et al., 2013), implying plagioclase had to be highly abundant in order to be detected. However, these studies predominantly used mixtures of minerals < 125 μm in grain size, designed to approximate regolith-covered bodies like the Moon, where intimate mixing and multiple scattering favor the more strongly absorbing mafic phases. Under these conditions, photons frequently interact with multiple mineral grains prior to exiting the surface. At increased grain size, inter-grain scattering between different mineral phases is reduced, increasing the likelihood that photons interact predominantly within a single mineral grain (Hapke, 2012). Since our samples have plagioclase grains at millimeter scale rather than tens of micron scale, the potential photon path lengths within individual plagioclase grains are increased, and photon interaction with adjacent mafic grains is reduced, increasing the likelihood of absorption by plagioclase. Additionally, the mafic minerals present in our intrusive samples do not absorb as strongly in the VNIR compared to pyroxene and olivine, commonly used in plagioclase mixture studies, whose intense ~ 1 μm absorptions more readily obscure the plagioclase band.

5.2.1.2. Plagioclase-Phyric Basalts

We hypothesize that confident detection of a 1.25 μm plagioclase band in basalts requires plagioclase grains to be considerably larger than any mafic minerals (i.e., megacryst/phenocryst > 1 mm vs. groundmass < 0.25 mm). Therefore, candidate rocks will likely have a porphyritic texture, few to no olivine or pyroxene phenocrysts, and plagioclase that has not undergone significant alteration. Our results show that only when plagioclase mixes solely with mafic groundmass is a strong 1.25 μm band present (Figure 8a, dashed blue line), but even in this ideal scenario a 1 μm band from the groundmass is visible and the spectrum does not show the symmetry of a typical plagioclase absorption band (Figure 2). The spectrum also resembles the broad band attributed to coarse olivine on Mars (Mustard et al., 2005). With the inclusion of minor quantities of pyroxene and olivine phenocrysts, the bulk spectra of the plagioclase-phyric basalts closely match spectra of mineral combinations that do not contain plagioclase. We show in Figure 8 that pyroxene plus olivine and pyroxene plus glass mixtures (B. H. N. Horgan et al., 2014; Singer, 1981) exhibit a 1–1.25 μm band shape similar to our basalt spectra. Even when plagioclase is present, the inclusion of olivine as a third component of plagioclase and pyroxene mixtures has been shown to mask the plagioclase band more efficiently (Cheek & Pieters, 2014). Therefore, the confident attribution of the 1.25 μm band to plagioclase requires careful consideration of these ambiguities, especially when interpreting Mars orbital VNIR spectra.

Rogers and Nekvasil (2015) showed that at sufficiently large grain size (~ 1 cm), plagioclase can be clearly detected and dominate the spectrum at 50 vol.% even when mixed with pyroxene. However, as noted in Eggers et al. (2021) and B. Horgan et al. (2023), the Type A pyroxene used in that mixture study has a significantly weaker 1 and 2 μm band (reduced spectral contrast) compared to other common types of pyroxene, even those detected in the vicinity of proposed plagioclase-phyric basalts on Mars. Evaluation of more plagioclase-phyric basalts or mixtures with greater compositional variety is necessary to establish more confident detection limits for plagioclase in basalts.

5.2.2. Suppression of Plagioclase Absorption via Weathering and Alteration

The 1.25 μm band can be obscured in the whole-rock spectrum with sufficient weathering. Between the two monzonite samples, ME-046 has a higher plagioclase iron content and higher plagioclase abundance yet lacks a 1.25 μm band, and spectral scans show few strongly absorbing plagioclase grains (Figure S9 in Supporting Information S1). In contrast, ME-048 has a clear 1.25 μm band in the whole-rock spectrum and strongly absorbing plagioclase grains in spectral scans (Figure 7). The primary difference between them is that the ME-046 spectral scan shows multiple veins and abundant chlorite throughout the sample, clear signs of hydrothermal alteration. This is not the case for ME-048, which shows rare examples of clay detections and no chlorite. We also observed this relationship between granites and granodiorites. Both rock types have similar plagioclase abundance and iron content, but granites showed few clear plagioclase absorptions in spectral scans, and granodiorites showed many. The difference was that most of the plagioclase within granites appeared more opaque and chalky, consistent with alteration into a clay mineral (likely montmorillonite). This is supported by spectral scans of granites which

yielded clear montmorillonite spectra (Figure 7, panel (g), cyan line; Figures S13, S14, and S16 in Supporting Information S1), unlike other samples.

5.2.3. Influence of Microtexture and Oxides on Absorption Bands

We hypothesize that discrete oxide grains significantly reduce the band strength of both plagioclase and mafic minerals in the felsic samples' whole-rock spectra. SR22-ML18 is a granodiorite in the weak absorption spectral group with similar plagioclase iron content, plagioclase vol.%, silica content, and mineral abundance to the other granodiorites, yet it shows no strong absorption features (other than a 1.9 μm band). In contrast, the granodiorites in the plagioclase-dominated spectral group have a clear 1.25 μm absorption along with minor absorptions at wavelengths $>2 \mu\text{m}$. SEM images comparing SR22-ML18 to a typical granodiorite are shown in Figure S20 in Supporting Information S1. Plagioclase grains in SR22-ML18 have sieve textures, and are associated with widespread, discrete oxide minerals. Two types of oxides were identified: Fe-rich, Si-depleted grains interpreted as magnetite and Ti–Ca–Si-rich grains interpreted as titanite (Figure S21 in Supporting Information S1). Other granodiorites have interstitial grains with discrete borders and few oxide grains. Plagioclase with sieve texture appears porous or spongy, due to the presence of numerous irregularly shaped inclusions made of glass or melt. This disequilibrium texture and oxide mineral abundance is in contrast with all other intrusive samples, and likely indicates some reheating or modification after initial solidification. During the reheating, iron may have been exsolved into the system, facilitating the formation of additional oxides. Previous studies have posited that spectrally neutral opaque oxide minerals reduce spectral contrast and suppress spectral features (Carli & Sgavetti, 2011; Carli et al., 2015; Cloutis et al., 1990b; Crown & Pieters, 1987; Moroz & Arnold, 1999; Nash & Conel, 1974; Scudder et al., 2021), and are more effective at reducing spectral contrast in felsic rocks given the higher abundance of translucent minerals (e.g., Moroz & Arnold, 1999; Nash & Conel, 1974). Though these studies were largely focused on mafic rocks, and intimate mixtures of grains at tens or hundreds of microns, we posit that the same effect may be occurring for sample SR22-ML18, differentiating it from the others in our study.

Because the mottled texture is essentially reducing the grain size of plagioclase in SR22-ML18, the plagioclase in the sample may be more subject to the effects of optical coupling, in which multiminerale grains reduce band depths (Hapke, 1993). When particles are more closely packed, photons are more likely to be scattered multiple times before escaping, and also are more likely to be trapped and absorbed internally. We favor the interpretation that oxides act as the dominant spectral suppressant over optical coupling mechanisms in this case because in SR22-ML18, the plagioclase grain sizes are on a similar order of magnitude as the other samples (i.e., the grains may not be small enough to experience major optical coupling effects). Further, hydrous mafic minerals do not bear mottled texture and are associated with higher concentrations of oxides, and their $>2 \mu\text{m}$ absorptions are also minimized. With the bands suppressed, we hypothesize the high albedo of the felsic and feldspathic grains (that together comprise $>90 \text{ vol.}\%$ of the rock) give rise to the strong blue-slope as lighter toned rocks reflect more light at shorter wavelengths in the VNIR range.

5.2.4. Influence of Plagioclase Chemistry on Detection

5.2.4.1. Anorthite Content

We do not observe a relationship between plagioclase band center and An# (Figure S19 in Supporting Information S1), in contrast with previous studies (Adams & Goullaud, 1978; Barthez et al., 2023). The An# of nine of our samples ranges from An_{24–90}, yet their band centers only range from 1.28 to 1.32 μm ; the highest An# sample (basalt, Drive 2, An₉₀) has a 1.29 μm band center. The relationship established in Adams and Goullaud (1978) relies upon a significant population of <30 An# plagioclase grains that are described as having broad, ill-defined absorption between 1.1 and 1.2 μm . The plagioclase in their study with An_{50–90} have more well defined 1.25 μm bands and considerable overlap in band centers, showing no clear trend associated with An#. Most of the plagioclase in our samples lie in a gap in their data between 30 and 50 An_{30–50}, have clear 1.25 μm Fe²⁺ plagioclase bands, and also show no relationship between An# and plagioclase band center. These results agree with discussion in Phillips et al. (2022, Supplemental) that the correlation between plagioclase An# and 1.25 μm band position is unreliable. These results also agree with Lundgaard and Tegner (2004) that the partition coefficient of Fe²⁺ may be independent of An# for $>\text{An}_{35}$.

Plagioclase in our study with $<\text{An}_{50}$ commonly shows a clear Fe-plagioclase band centered at 1.25 μm . Out of the 13 samples that underwent EPMA analyses, 11 bear plagioclase with $<\text{An}_{50}$. Of those 11, the spectral scans of

eight show clear 1.25 μm bands associated with individual plagioclase grains. Adams and Goullaud (1978) state plagioclase with compositions between An_{50} and An_{90} is likely not detectable, but our results clearly show detection outside this limit. Slower cooling rocks in lower temperature settings tend to have lower plagioclase $\text{An}\#$, so our results imply plagioclase should be detectable in felsic rocks.

5.2.4.2. FeO Content

For coarse-grained felsic rocks in our sample set, the lowest FeO concentration associated with a detectable 1.25 μm plagioclase band is 0.13 wt.% FeO (Figure 6). This limit was determined based on the chemistry and mineralogy of the rocks in the plagioclase-dominated spectral group, which have strong 1.25 μm bands. The 0.13 wt.% FeO value defines an empirical lower bound for possible detection, while band strength above this value remains controlled by plagioclase abundance, grain size, alteration, and associated mineral phases. Rocks in the plagioclase-dominated and weak absorption spectral groups have similar plagioclase FeO contents and abundances, yet granites in the weak absorption group exhibit weak to absent whole-rock 1.25 μm bands, likely due to alteration. Isolated, minimally altered plagioclase grains within these granites show clear 1.25 μm absorptions in spectral scans (Figure 4, Figures S14–S17 in Supporting Information S1), suggesting that less weathered equivalents would exhibit detectable bands at slightly lower FeO contents (~ 0.12 wt.%). Only for the hydrous mafic-dominated spectral group made up of tonalites, with plagioclase depleted in iron (< 0.04 wt.% FeO), is there a total absence of plagioclase absorption both in the whole-rock spectrum and in spectra from individual plagioclase grains. Previous results report a cutoff of 0.05 wt.% FeO (Bell & Mao, 1973), similar to our results.

5.2.5. Summary of Conditions for Plagioclase Detections in Whole Rocks

In summary, we suggest four standards for plagioclase detection in whole rocks established by our results and previous studies, provided the rocks have not undergone significant weathering/alteration and the plagioclase is not depleted in iron: (a) When plagioclase is fine-grained (< 0.25 mm), > 85 vol.% plagioclase is required for confident detection, particularly if the other phases in that mixture are olivine, pyroxene, or other strong absorbers in the VNIR wavelength range. This has been shown previously for fine-grained powders/regolith (Cheek & Pieters, 2014; Serventi et al., 2013), and our results show that this rule likely also applies to fine-grained extrusive rocks as well given the lack of 1.25 μm features in almost all extrusive rocks (Figure S18 in Supporting Information S1). (b) In felsic rocks, plagioclase can be detected at much lower abundances (< 35 vol.%), even when mafic hydrous minerals (e.g., amphiboles and Fe-bearing micas) are present and at similar grain size, but plagioclase must be coarse-grained (mm to cm scale). This can include effusive volcanic rocks, like plagioclase-phyric dacites (Barthez et al., 2026). (c) Plagioclase can be detected at lower bulk abundances (< 50 vol.%) in mafic rocks but requires much larger (mm to cm scale) plagioclase grains compared to mafic grains (< 0.25 mm). (d) VNIR plagioclase detection is ambiguous when pyroxene or olivine phenocrysts are present and at similar size (within $\sim 10\%$; 1 mm pyroxene to a 10 mm plagioclase) to plagioclase grains.

5.3. Accuracy of TIR Models of Felsic Rocks

Our results show that TIR unmixing models are capable of reproducing modal mineralogy within 20%, and the majority of models are within 15% of XRD-derived mineral abundance, similar to successful models in past unmixing experiments (Feely & Christensen, 1999; Hamilton & Christensen, 2000; Scudder et al., 2021; Wyatt et al., 2001). In order to achieve accurate fits to the felsic rock emissivity spectra, we found we had to refine the minerals in our spectral library. This is in contrast to previous studies focusing on mafic and intermediate effusive samples, where fits improved with greater variety of minerals in the TIR endmember library (e.g., Scudder et al., 2021). For instance, the detailed library of Scudder et al. (2021) provided excellent estimates of mineral abundances for basaltic and andesitic volcanic rocks, but did not yield accurate estimates for our samples, despite containing most of the minerals we used in our refined spectral library. We hypothesize that the less accurate models in our study may in part be the result of using bulk, whole-rock samples rather than measuring pelletized samples which have a more even volume distribution of minerals (Scudder et al., 2021) and would be more comparable to XRD sample-processing techniques. The coarse-grained nature of the majority of our rocks may make them even more susceptible to inaccurate fitting, due to a lower signal-to-noise ratio that reduced the ability for the model to discriminate diagnostic mineral bands, as library minerals used for the fitting tend to be a significantly smaller grain size than our samples. The effects observed in whole crystalline rocks in this study

should be considered when evaluating linear deconvolutions of thermal infrared data of planetary surfaces acquired from orbit.

We find that samples with the lowest abundance of primary hydrous mafic minerals and secondary minerals (granites) tend to have the most accurate fits among intrusive rocks. The hydrous mafic minerals and clays are <10 vol.% individually, and can sum to >20 vol.% of their host rock. Almost all models assign a value of ~10 vol.% for minerals that are not feldspars or quartz; a greater abundance of mafic or secondary minerals in the samples led to a greater error in the TIR models in our study. Our results are consistent with previous analyses that show that at <10 vol.%, biotite and chlorite have no observed characteristic spectral features (Feely & Christensen, 1999). These minerals tend to be more prevalent in granodiorites and monzonites, which may be why the model fits for these rocks tend to have greater overestimation of plagioclase abundance. Even so, the abundances are within approximately a 5–10 vol.% error of the actual total abundance of hydrous minerals, but the models do not accurately identify the type of hydrous mineral and at times mistakes it for K-feldspar glass. Alternatively, Ramsey and Christensen (1998) also state that the more translucent nature of quartz makes it less linear in emission spectra, so it could be that the abundance of more translucent felsic minerals in the samples also contributes to the error. In a future study, we intend to investigate further whether the coarse nature of the samples, presence of hydrous mafic minerals or clays, abundance of translucent minerals, or the need for a broader spectral library more strongly influences spectral unmixing accuracy.

5.4. Detectability of Plagioclase-Bearing Rocks From Orbit on Mars

Our results suggest that plagioclase may be detected from orbit in coarse-grained felsic and potentially certain types of mafic rocks. A caveat is that minerals like amphibole are unexpected on Mars and have not been observed in abundance, so our samples are not a perfect comparison to Mars rocks. However, even in the presence of these hydrous mafic minerals, we show that plagioclase is still likely responsible for the 1.25 μm absorption. Thus, detection of a 1.25 μm band in VNIR could be evidence of (a) feldspathic rocks like anorthosite (≥ 90 vol.% plagioclase); (b) mafic rocks with large plagioclase phenocrysts (mm to cm scale), minimal mafic phenocrysts, and fine-grained (<0.25 mm) mafic minerals; as well as (c) coarse-grained intrusive felsic rocks with plagioclase abundance >35 vol.% (e.g., granodiorite, monzonite). If the outcrops are of a sufficient spatial scale, TIR data would help determine which rock type is present, where spline-fit minima of <9.3 μm would provide support for the detection of plagioclase-bearing felsic rocks, while >9.7 μm would suggest mafic rocks or feldspathic rocks (i.e., plagioclase cumulates).

We also place some constraints on what types of felsic rocks are less likely to be detectable in VNIR data. Most notably, no granites in our sample set exhibit a strong 1.25 μm band. However, the granites show the clearest and strongest clay (likely montmorillonite) VNIR signatures of all our samples, so we cannot rule out possible plagioclase detection in un-weathered granitic rocks, such as might exist on Mars. Because alteration can mask the 1.25 μm band in large plagioclase crystals, altered plagioclase-bearing rocks on Mars are unlikely to be detectable. A similar effect is observed in Jezero crater basaltic andesite lava flows, where VNIR absorptions from plagioclase crystal laths are obscured by a broad 1.15 μm band due to secondary clays that were formed by low degree alteration (B. Horgan et al., 2023; Mandon et al., 2023).

5.5. Comparison to Mars Feldspar Detections

The Nili Patera caldera within Syrtis Major exhibits strong 1.25 μm features and has been interpreted as anorthositic (Carter & Poulet, 2013), a felsic rock potentially with cracks infilled with basaltic sand (Eggers et al., 2021; Wray et al., 2013), or a plagioclase-phyric basalt (Rogers & Nekvasil, 2015). In spatially resolved THEMIS images, Rogers and Nekvasil (2015) argue that TIR band positions (~9.8–10.1 μm) are inconsistent with felsic rocks like granite or quartz monzonite (<9.3 μm), but are consistent with anorthosite or basalts (~9.8–10.4 μm). At a few locations, Rogers and Nekvasil (2015) also argue that the geologic context favors an eruptive rather than plutonic environment, thus supporting a plagioclase-phyric basalt. Our results demonstrate the plausibility of a plagioclase-phyric basalt interpretation, though it is worth noting basalts and anorthosites are difficult to distinguish at THEMIS resolution (Phillips et al., 2022; Rogers & Nekvasil, 2015). Additionally, some exposures of possible felsic materials may not be spectrally resolved in THEMIS data. Eggers et al. (2021) argue that the feldspathic unit's polygonal fracturing could be infilled with basaltic sand, thus masking the possible felsic nature of the rock. However, if basaltic sand were present, one might expect 1 μm signatures from pyroxene

or olivine rather than the observed pristine 1.25 μm feature. Importantly, TIR band positions as low as $\sim 9.4 \mu\text{m}$ were detected in the Nili Patera region, and though the TIR band position for felsic rocks is expected to be below $\sim 9.3 \mu\text{m}$, we speculate the proposed basaltic sand could be shifting the TIR band position to longer wavelengths. The complexity of this region and spectral ambiguity makes it difficult to rule out any of the current hypotheses.

In the Terra Cimmeria/Sirenum region of Mars, the combination of VNIR plagioclase detections and MIR data has been used to infer the presence of intermediate rocks (Payré et al., 2022). Payré et al. (2022) used the weighted absorption center (WAC) method to calculate MIR band position, which is a similar method to the spline-fit minima used in our study and others (e.g., Phillips et al., 2022; Rogers & Nekvasil, 2015). The WAC method generates band positions near $\sim 10.1 \mu\text{m}$ for basaltic compositions and between ~ 9.4 and $9.7 \mu\text{m}$ for monzonite, dacite and granodiorite. The detection of ~ 9.6 – $9.8 \mu\text{m}$ band positions for a few outcrops indicates an intermediate composition, though most detections are between ~ 9.9 and $10.05 \mu\text{m}$, which is closer to the basaltic range. The granodiorites and monzonites in our sample set share 1.25 μm band shapes and TIR band position similar to those Payré et al. (2022) detections, substantiating the interpretation of evolved intermediate or felsic rocks in some of the locations. Plagioclase detection limits in coarse-grained intermediate rocks, like diorite, are not well established, so more work needs to be done to establish the physical and chemical characteristics needed for intermediate rocks to display a 1.25 μm band associated with plagioclase.

Proposed origins for plagioclase detections on the wall of Valles Marineris include a plagioclase-bearing ignimbrite sheet or lava flow buried by subsequent volcanism (Flahaut et al., 2023), incipient craton formation, or fractional crystallization of basaltic material (Viviano-Beck et al., 2017). Of these hypotheses, we do not favor an ignimbrite origin, as our and previously published plagioclase-bearing ignimbrite and tuff samples show no absorption bands that could be attributable to 1.25 μm plagioclase absorption, and their spectra tend to be bland in the 1–2 μm region other than hydration bands (Figure S18 in Supporting Information S1; Henderson et al., 2021). Given the heterogeneous nature and high glass content of ignimbrite flows, it seems unlikely this would favor a largely plagioclase-phyric nature and a detectable 1.25 μm band.

Exposures of widespread feldspathic material have been detected at both the Hellas and Argyre basins (Phillips et al., 2022, 2025), consistent with the widespread impact excavation and exposure of a large crustal component of plagioclase-rich material, such as anorthosites or other plagioclase cumulates. In this case, the TIR data ($\sim 10 \mu\text{m}$ band position) do not support a felsic composition.

There are clear examples of evolved lithologies on Mars from observations of samples and in situ observations by the *Curiosity* rover with sufficient plagioclase abundance, iron content, and grain size to be detected via VNIR spectroscopy. In Gale Crater and in meteorite NWA 7034, evolved samples have plagioclase abundances of 55–80 and 28–70 wt.% feldspar based on mineral count and CIPW normalization calculation, within the detection limit of plagioclase in VNIR based on our samples (Cousin et al., 2017; Hewins et al., 2017; Sautter et al., 2015, 2016; Udry et al., 2018). Some of these samples were coarse-grained or had large plagioclase phenocrysts in a fine-grained matrix, grain sizes ideal for detection. Pre-Noachian (>4.1 Ga) monzonitic clasts in NWA 7533 (Hewins et al., 2017; Humayun et al., 2013) and recently reported granitic clasts dominated by quartz, plagioclase, and K-feldspar (Malarewicz et al., 2025) have plagioclase iron content of 0.15–0.83 wt.% FeO, all at or above the detection limit of our samples. Some clasts even have no mafic minerals, optimal for VNIR plagioclase detection. Since Mars rocks likely have more iron-rich plagioclase and fewer primary hydrous minerals (Hewins et al., 2017; Phillips et al., in review), there could be an even greater chance of detection at lower abundances on Mars as increased iron increases plagioclase band depth and detectability (Carli et al., 2015; Carli & Sgavetti, 2011; Serventi et al., 2013). Given the possibility of lower detection limits of plagioclase feldspar in felsic rocks argued for in this paper and the diversity of evolved Martian lithologies, we advocate for considering a wider range of lithologies when evaluating 1.25 μm detections in orbital data from Mars.

The in situ observations and proliferation of orbital detections of plagioclase feldspar associated with ancient terrain provide strong evidence for an early and extensive evolved component of the martian crust. Exploration of locations with coherent vertical exposures of ancient crust that coincide with plagioclase detection, such as Hellas Basin or Valles Marineris, would elucidate the complexity and evolution of the Mars crust, applicable also to Earth's early crust which has long since been recycled (Payré et al., 2024).

6. Conclusions and Implications

With a coordinated set of VNIR and TIR spectroscopy, supported by XRF, XRD, EPMA, and microscopic techniques, we investigated the spectral properties of a wide range of intrusive and extrusive plagioclase-bearing igneous rocks. Our results show that plagioclase signatures in felsic rocks like granodiorite and monzonite (35–50 vol.% plagioclase) exhibit plagioclase absorption bands that could be used to detect these rocks from orbit even when accompanied by hydrous mafic minerals. We also find that plagioclase-phyric effusive rocks (e.g., basalts, obsidian) can exhibit the 1.25 μm plagioclase absorption band if plagioclase grains are large relative to mafic minerals (pyroxene, olivine), similar to previous results (Barthez et al., 2023, 2026). These results expand the diversity of rock types detectable from orbit, including plagioclase-phyric effusive rocks and coarse-grained felsic crustal rocks.

A number of important factors are relevant for plagioclase detection:

- Plagioclase FeO content >0.13 wt.% and grain size (mm-scale or larger) are critical characteristics for plagioclase detection in the VNIR, where large grain sizes (mm-scale) are necessary when plagioclase is not at high abundance (<85–90 vol.%).
- A wide range of plagioclase chemistries ($\text{An}_{25-47,90}$) can produce a 1.25 μm absorption provided the plagioclase is not depleted of iron. Slower cooling rocks in lower temperature settings tend to have lower plagioclase An#, so our results imply plagioclase should be detectable in intrusive felsic rocks.
- Alteration can obscure the 1.25 μm plagioclase absorption in felsic and basaltic rocks. As a result, plagioclase grains with similar iron content can have drastically different spectral character if the plagioclase is intimately associated with alteration.
- For an unambiguous 1.25 μm detection from plagioclase-phyric basalts, the rock must be almost devoid of pyroxene and olivine phenocrysts (i.e., grain sizes $\ll 1$ mm).
- Opaque oxide minerals may be particularly effective at subduing absorption bands in felsic rocks, especially in cases where oxides have exsolved from mineral grains and are intertwined with host minerals at fine scales.
- Even if mafic hydrous minerals (e.g., amphibole, biotite) comprise ~ 20 vol.% of the sample, the plagioclase band is still detectable if the other conditions are satisfied.

When considering detection from orbit:

- Multiple lithologies can yield a 1.25 μm absorption band from plagioclase, but clear detection is only likely for: (a) plagioclase-rich crust (e.g., anorthosites or other plagioclase cumulates), (b) intrusive felsic rocks with limited alteration and plagioclase not depleted in iron (e.g., granodiorites), and (c) plagioclase-phyric basalts with little or no mafic phenocrysts. Our study does not constrain the possibility of plagioclase detection in intermediate rocks, for which more analyses are needed, though other studies show plagioclase-phyric dacites can exhibit a plagioclase band (Barthez et al., 2026).
- MIR spectra can be used to distinguish felsic (granite, granodiorite, monzonite) and mafic (anorthosite, basalts) plagioclase-bearing rocks with similar 1.25 μm absorptions based on the position of the fundamental Si-O band in MIR spectra.
- However, it is important to note that at THEMIS spectral resolution, felsic rocks can be spectrally similar to one another despite a difference in silica as high as ~ 15 vol.%, so THEMIS likely cannot be used to differentiate, for example, granite from monzonite.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data archiving of laboratory spectra collected in this study, band parameters, and chemical data are publicly available on Mendeley Data (<https://data.mendeley.com/preview/jd8z2s8mk8?a=64657873-490c-4e01-bfe3-31dc94b06bf7>). All laboratory endmember spectra and associated metadata can also be found in Mendeley Data repository.

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