

Constraining the Hydration State of the Phyllosilicate
Deposits of Eastern Valles Marineris Mars

Craig A. Rezza

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Abstract

Sounding radar is an invaluable tool for understanding the properties of the surface and subsurface materials of planetary bodies. Clay materials offer a direct link to the history of water presence at the time of formation, and thus are imperative to study. A study has found that the bound water of these deposits render radar observations ineffective, as the water presence absorbs the radar signal beyond detection (Stillman & Grimm 2011). However, at Aurorae Planum, the plateau south of Ganges Chasma, in Eastern Valles Marineris, basal reflections are still observed, despite the presence of widespread clay deposits in the region. We conduct dielectric laboratory experiments on a terrestrial analog clay sample at varying levels of dehydration in order to constrain dielectric properties sufficient enough to allow transmission of SHARAD radar. In addition to this, we utilize HiRISE and CRISM data to draw correlations between the clays and the radar observations. We determine that the reason behind this contradiction is two-fold. We find that following a catastrophic flooding event, leftover pooled water began to evaporate, providing the necessary mechanism for desiccation due to water table retreat to occur, minimizing the influence of bound water on the incident radar waves. This desiccation must have resulted in a water mass loss of at least $\sim 8\%$ from our control measurements. In addition, we find the clay layers to be between 1.5-3 m thick, implying that the deeper radar reflections we observe are from a lower unit, accounting for a reflection depth of ~ 16 m. Therefore it is a combination of desiccation due to water table retreat, via evaporation, and thin clay layering that accounts for this contradictory region.

Dedication

I dedicate this thesis to my dedicated and supporting mother and father, Patricia and Peter Rezza, who have been my biggest supporters in pursuing my passion for space and science ever since Space Day in kindergarten. If it was not for you encouraging me to follow my dreams, I would have never made it as far as I have come now. I am eternally grateful for your love and support. To my sister Angela for providing countless emotional support pictures of Tuukka, Daisy, and Bambi, and to my brother Adam for listening to me rant about my research.

I additionally dedicate this work to my incredible lab mates in the DICE lab who have been amazing friends to me through my time in Toronto. As well as my friends from afar who helped keep me grounded throughout the COVID-19 quarantine. Each and every one of you held a small piece that led me to my success in completion of this study.

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1 Introduction

Understanding surface and subsurface materials of Mars is a key to understanding its present climate and unraveling its climatic history. Sedimentary deposits may especially provide evidence of habitability, water cycle variability, and active geologic processes in the past. Utilizing sounding radar to observe these deposits allows us to constrain their dielectric properties, which will allow inferences into the materials' bulk density and even bound water content.

The phyllosilicate deposits of Mars represent the outcome of aqueous conditions during the early periods of the planet's history. To study these conditions and the subsequent history, we characterize the bound water content of relict soils, and geologic evidence of surface and subsurface water that was on the surface during the Noachian epoch (4.1-3.7 Gya), one of the earliest periods of Mars history that is characterized by the ample presence of liquid water.

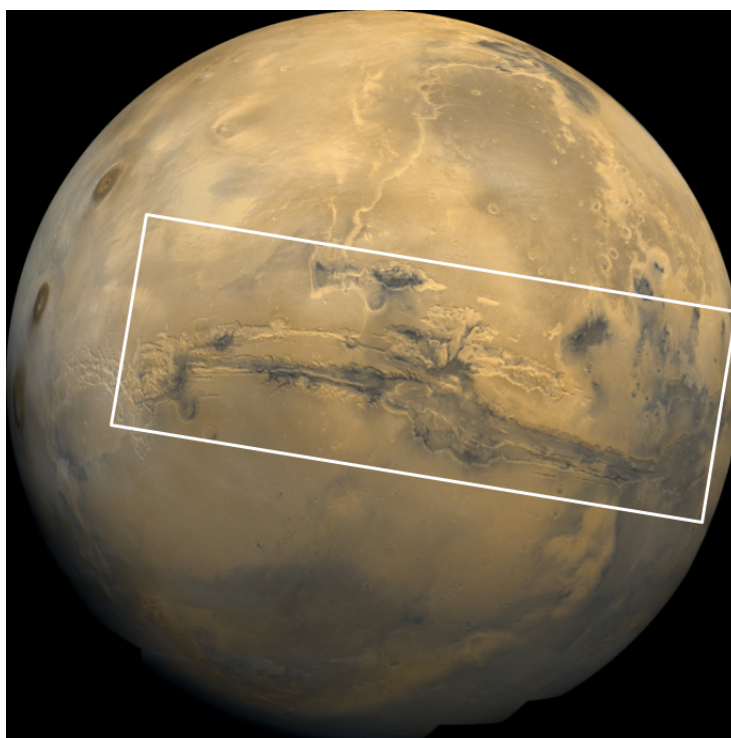


Fig. 1.1: Overview of Valles Marineris

An orbital image of Valles Marineris taken by Viking-1. Valles Marineris is represented within the white box. (image credit: NASA)

1.1 Geologic Setting

1.1.1 Valles Marineris

Valles Marineris is one of the most geologically interesting sites to study in the solar system (Fig. 1.1). Located in the Tharsis region of Mars, it is a series of canyons formed through a complex history of tectonic formation beginning in the Noachian epoch and continuing into the Hesperian epoch (3.7-3.2 Gya) (Andrews-Hanna 2012). The Noachian epoch, and to a slighter degree the Hesperian epoch are key time periods for Valles Marineris. These epochs were warm and wet periods of Mars' history (Mangold *et al.* 2004, Quantin *et al.* 2005). In this climate, the plateaus between the canyons would experience frequent precipitation, driving wide-spread fluvial and lacustrine activity (Weitz *et al.* 2010). This water presence served to bring sedimentation to the plateaus of Valles Marineris, which are further chemically altered in such a wet environment.

1.1.1.1 History of Layered Deposits and Phyllosilicates

Especially important to us are the light toned deposits (LTDS) of Eastern Valles Marineris, which are rich with Al and Fe/Mg phyllosilicates, as has been identified using the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), which has a Hyperspectral range from 362-3920 nm (Murchie *et al.* 2007), Le Deit *et al.* 2012) (Fig. 1.2). The absorption bands for these phyllosilicates appear at 1.9 μm and 2.2 μm for Al phyllosilicates and at 1.9 μm and 2.3 μm for Fe/Mg phyllosilicates (Le Deit *et al.* 2010, Le Deit *et al.* 2012). During the Noachian Epoch, the surface materials were altered by diagenesis and pedogenesis, through precipitation and lacustrine processes (Le Deit *et al.* 2010, Le Deit *et al.* 2012, Ehlmann *et al.* 2013). This alteration occurred in a low temperature, pH neutral environment, yielding finely crystallized Al-rich phyllosilicate deposits (Le Deit *et al.* 2012).

Phyllosilicates are constructed of octahedral sheet structures. Within the Al, Fe, and Mg molecules are trapped layers of OH and O molecules (Brown *et al.* 1984) (Fig. 1.3). The

presence of these OH layers easily allow H_2O molecules to be trapped between the sheets, (Kuligiewicz & Derkowski 2017). These sheets can hold these bound water molecules well past 100 °C, such as the case with certain Fe/Mg based compositions which only begin to break down these OH bonds towards 300 °C (Mering 1946). Such bonds allow phyllosilicates to become highly adsorbent to water.

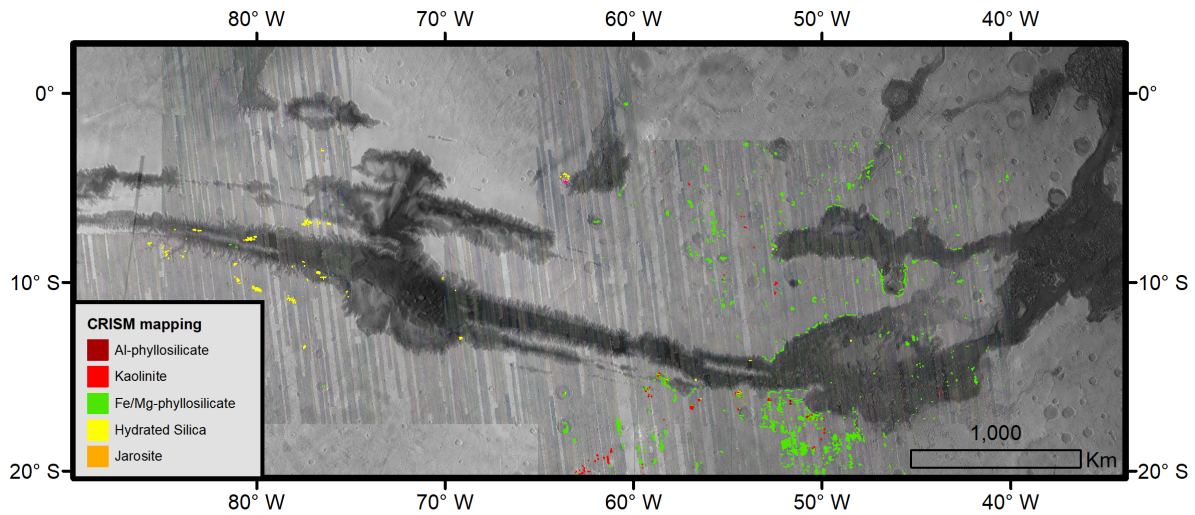


Fig. 1.2: CRISM Map of Valles Marineris

CRISM Map highlighting surface detections of various hydrated minerals and phyllosilicates. The detections are observed from a Hyperspectral band of 362-3920 nm. The detections are identified according to methods developed by Viviano *et al.* 2014, and then mapped locationally onto a basemap based from MOLA elevation data. (Unpublished, credit to Christina Viviano)

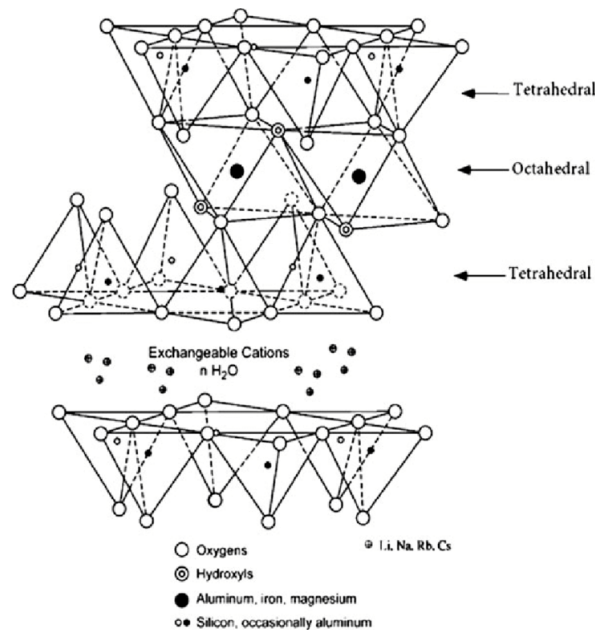


Fig. 1.3: Phyllosilicate Sheet Structure

Sketch of phyllosilicate sheet structure that highlights the shape of the crystal lattice and the layer of exchangeable H_2O cations between the lattice. Used with permission of Khalid *et al.* 2016.

These newly deposited surface materials locally experience alteration from surface runoff over the mid to late Hesperian period (3.4-3.2 Gya), forming the LTDs observed on the modern surface in a cooling and drying environment (Le Deit *et al.* 2012). Some of these LTD examples have been cited as polygonally fractured units (order 10 m), potentially formed due to hydration and dehydration cycles (Le Deit *et al.* 2012) (Fig. 1.4). The alteration primarily yielded Fe-sulfates as well as, in some regions, Fe/Mg rich phyllosilicate deposits (Le Deit *et al.* 2010, Weitz *et al.* 2010). Airfall dust and basaltic ash covered these Noachian and Hesperian phyllosilicates. Through the late Hesperian into the Amazonian epoch (3.2 Gya - Present), erosional processes begin to exhume the Noachian Fe/Mg and Al deposits, bringing them to the surface (Le Deit *et al.* 2010, Le Deit *et al.* 2012).

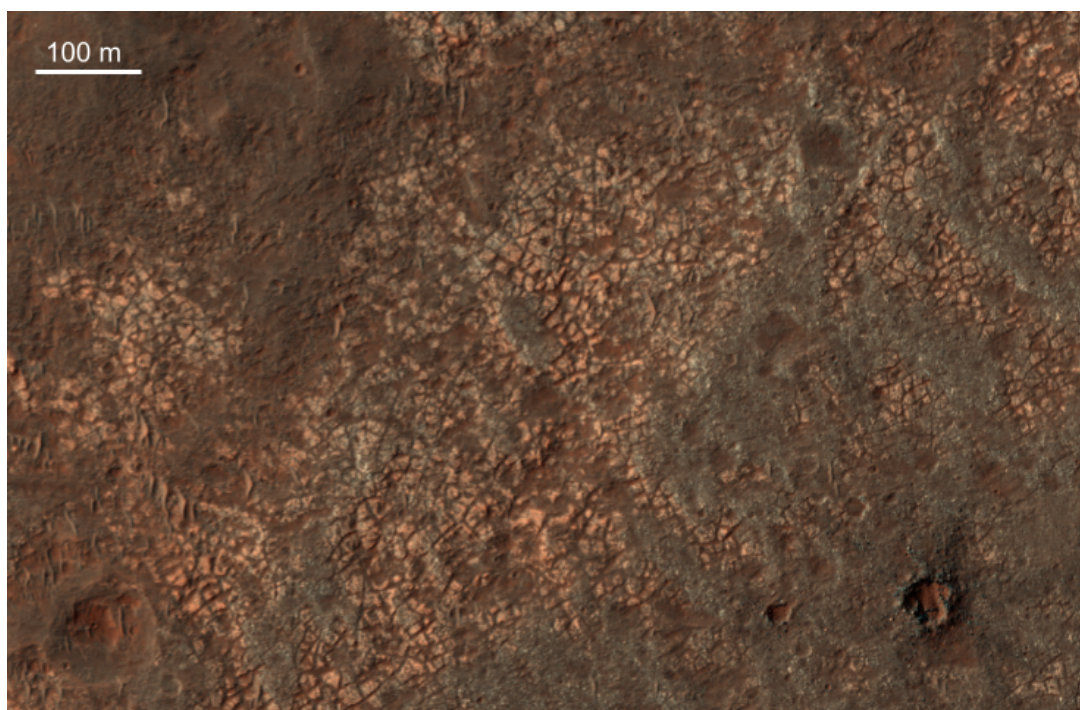


Fig. 1.4: Polygonal Fracturing on Mars

Merged RGB Image of HiRISE image ESP_063471_1690_MRGB displaying polygonally fractured terrain.
(NASA/JPL/University of Arizona)

1.1.2 Aurorae Planum

One such location where these Fe/Mg phyllosilicate deposits are observed is on Aurorae Planum. Aurorae Planum is the plateau in the northeast of Valles Marineris located between Ganges Chasma and Capri Chasma (Fig. 1.5). The surface of the plateau is

primarily composed of middle and late Noachian highland units (Tanaka 2014). The majority of the plateau is composed of relatively smooth layered deposits with few craters and locally fractured units (Witbeck *et al.* 1991).

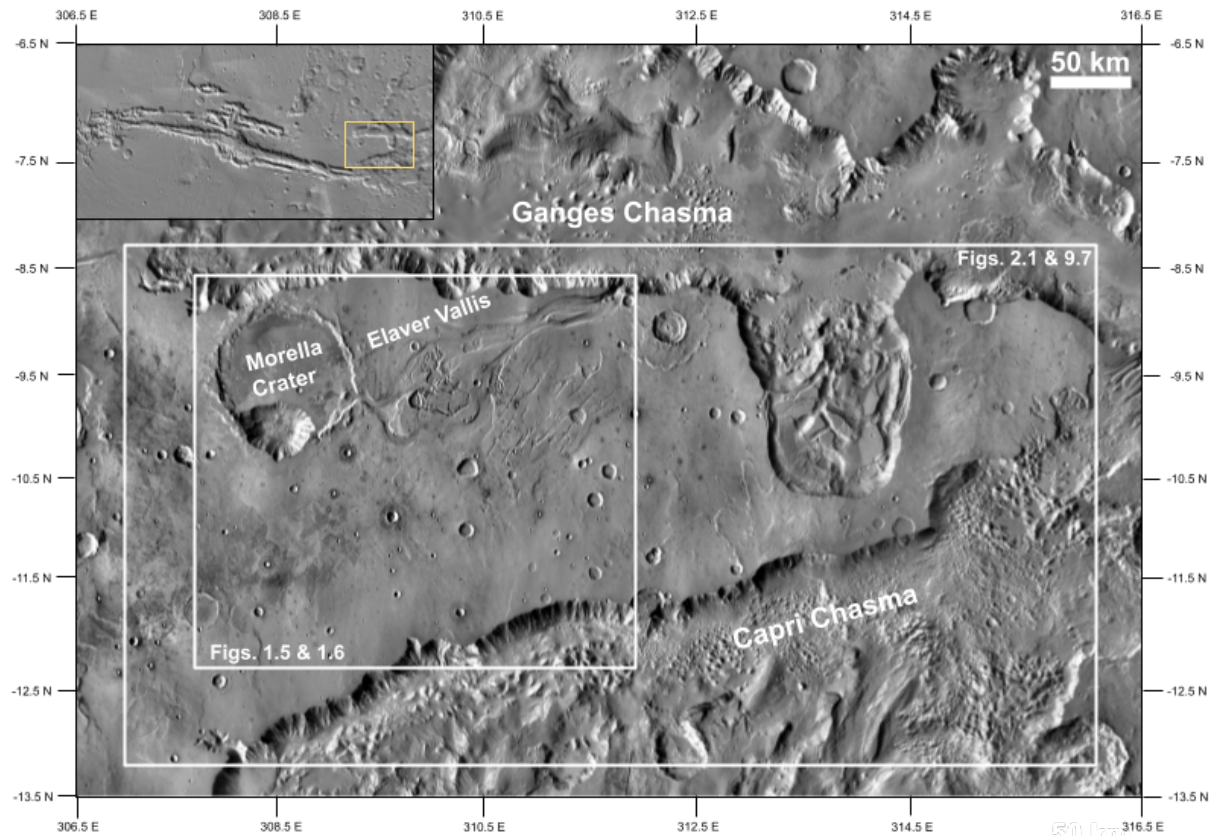


Fig. 1.5: Aurorae Planum Context Map

Map of the Study Region, Aurorae Planum. Basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

1.1.2.1 Morella Crater and Elaver Vallis

One of the key features of Aurorae Planum is Morella Crater, located in the north of the plateau (Fig. 1.5). Morella Crater is a 75 km diameter impact crater, that features a deep collapsed pit, Ganges Cavus. Several reports have theorized that Ganges Cavus was the source for a massive surge of pressurized groundwater that began to fill Morella Crater, some time in the mid to late Hesperian (Coleman *et al.* 2007, Komatsu *et al.* 2009). The outflow waters are theorized to have eventually breached the eastern wall of the crater (Fig. 1.6) causing a megaflood that devastated the sediments of the plains to the east, carving out a ~150 km long system of channels: Elaver Vallis (Coleman *et al.* 2007,

Komatsu *et al.* 2009, Coleman 2013) (Fig. 1.5).



Fig. 1.6: Morella Crater and Elaver Vallis Context Map

Map centered around Aurorae Planum, spatially referenced in Fig. 1.5. Basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

The flooding event lasted for 6.4-7.5 days with a discharge rate between 1.94×10^7 and $3.51 \times 10^7 \text{ m}^3 \text{ s}^{-1}$. Over this period, Elaver Vallis was carved out in two separate channels formed around a central island, one primary channel in the north and a secondary channel in the south (Fig. 1.6). At the time of the initial breach, both channels were excavated by the flood waters. Mars Orbiter Laser Altimeter (MOLA) (Smith *et al.* 2001) data of Aurorae Planum shows that The primary channel is more deeply cut than the secondary channels, starting from the breach of the crater at ~ 1500 m, and lowering to around 1100 m before spilling into Ganges Chasma (Fig. 1.7). The two parts of the secondary channel, both in the north and south are between 1500 and 1600 m in elevation. In between the primary and secondary channel is an island between 1700 and 1800 m in elevation. This height of 1800 m sets a lower bound on the minimum flood height of the initial flood, implying the surrounding landscape before the flood was roughly around 1700-1800 m in elevation. After the first 1 to 1.7 days, the flood levels lowered beyond the elevation of

the southern channel, funneling flood waters through the northern channel only, carving it deeper over the remaining 6 to 5.3 days. (Coleman 2013). This recession is also apparent in the northern channel as a higher elevation portion of the channel appears to be carved out (Fig. 1.6).

A maximum bound for the flood height is set by the minimum elevation of Morella craters rim, ~ 1900 m. To the northeast of Morella crater, there is a significant flat region spanning about 10 km across the plateau (Fig. 1.6). The northern flatlands remain at ~ 1593 m in elevation across the majority of the span (Fig. 1.7). At the southern edge of the flatlands, the terrain drops off to ~ 1300 m, leading into Elaver Valles. Further, southeast of Morella crater is a basin that is slightly higher elevation than the flatlands, at an elevation up to 1800 m. It is flanked on either side by higher elevation features, steeply rising up to 1850 and 1900 m in elevation (Fig. 1.7). The basin feeds into the southern channel of Elaver Vallis through a distinct outlet channel not previously reported by Coleman 2013 (Fig. 1.6). We have measured the basin's slope feeding into the channel to be quite shallow with a grade of $\sim 0.2\%$.

Another competing study finds that instead of pressurized water, Ganges Cavus served as a volcanic caldera, filling the crater with low viscosity lava that is responsible for carving Elaver Vallis (Michalski 2021, in review). In this study, we test the first hypothesis, which is, so far, consistent with decades of investigations and can potentially explain the clay deposits in a way that lavas cannot.

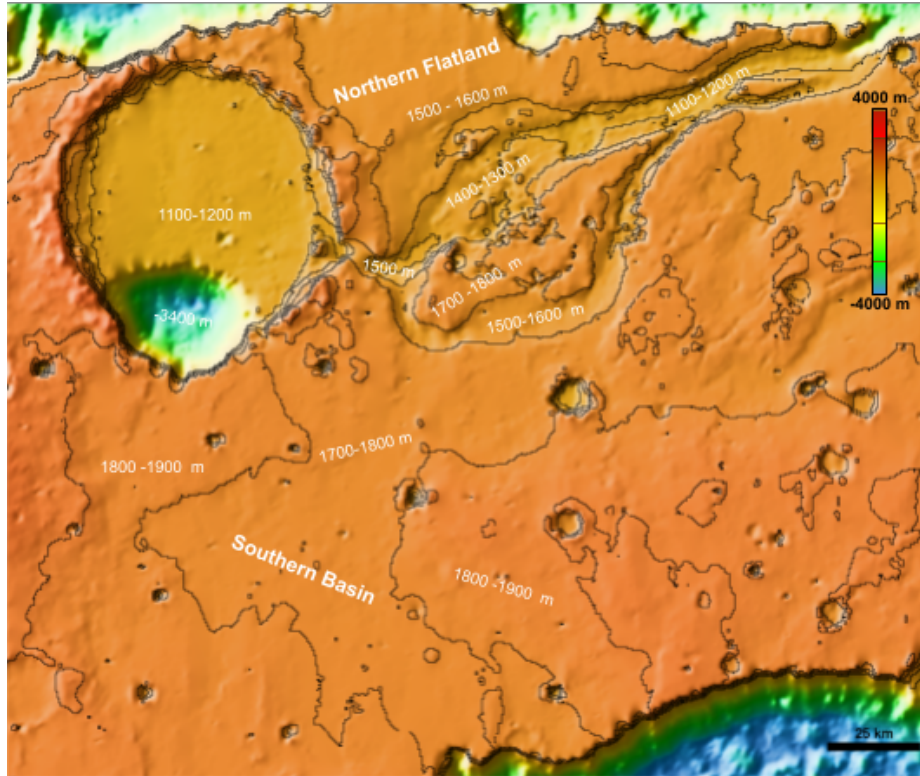


Fig. 1.7: Flood Region Elevation Map

HRSC/MOLA colorized relief map (USGS Astrogeology Science Center) of Morella flood regions overlain by MOLA 128ppd contour elevation map from 1100-2000 m (MOLA Team Washington University, St. Louis).

2 Background

2.1 Shallow Radar at Aurorae Planum

To achieve a better understanding of subsurface and surface materials, radar sounding instruments are commonly used. The Shallow Radar (SHARAD) instrument aboard the Mars Reconnaissance Orbiter (MRO) (Seu *et al.* 2007) is one such radar sounder that has been used extensively and successfully for studies of Mars' subsurface and the electrical properties of its sediments (Campbell *et al.* 2008, Carter *et al.* 2009, Stillman & Olhoeft 2008, Smith *et al.* 2016, etc.). SHARAD is a dipole radar instrument that generates a chirped $80 \mu\text{s}$ pulse with a center frequency of 20 MHz from an orbiting altitude of ~ 300 km (Seu *et al.* 2007). Each electromagnetic pulse emitted by the antenna is reflected back to the instrument from some layer of the surface or sub-surface. These reflections will occur at interfaces where there is a sudden transition between the physical properties

of the two mediums, such as a change in their dielectric properties (Section 2.2), water content, or grain size. The time delay and voltage of each returned signal is recorded and processed to resolve along track with a spatial resolution of 0.3-1 km along track and 3-6 km across track and a vertical free space resolution of 15 m (Seu *et al.* 2007).

2.2 Complex Permittivity

It is necessary for radar instruments to measure the time delay, as every material has its own inherent dielectric properties that dictate how electromagnetic radiation travels through the material. As light enters a new medium from free space, its travel velocity (c) will be slowed down. The extent of this inhibition is controlled by the medium's relative permittivity (ϵ_r^*). ϵ_r^* defines how well bound charges in the material separate under the influence of an electric field (Stillman & Olhoeft 2008). It is a unitless complex number that is related to the permittivity of free space (ϵ_0) such that:

$$\epsilon_r^* = \frac{\epsilon^*}{\epsilon_0} = \epsilon_r' - i\epsilon_r'' \quad (2.1)$$

Where ϵ^* is the absolute permittivity of the material. ϵ' is the real part of the permittivity and is a measurement of how the material refracts and slows the phase velocity of the electric component of the electromagnetic wave. The imaginary part of the permittivity (ϵ'') is a damping factor that accounts for energy lost within the material (Stillman & Olhoeft 2008). ϵ_0 is equivalent to $8.85418782 \times 10^{-12} \text{ m}^{-3} \text{ kg}^{-1} \text{ s}^4 \text{ A}^2$.

The speed of light in the dielectric material is represented by:

$$c = \frac{1}{\sqrt{\epsilon^* \mu^*}} \quad (2.2)$$

Where μ^* is the absolute magnetic permeability of the material.

2.2.1 Permittivity For Nonhydrated Materials

For most geologic materials, ϵ' has a value between 1 and ~ 15 . This value is mostly based on density (ρ) for non-hydrated materials, calculated through the empirical equation (Ulaby *et al.* 1988):

$$\epsilon' = 1.96^\rho \quad (2.3)$$

with air having a value ~ 1.0006 , water ice at ~ 3.15 (Grima *et al.* 2009), and basaltic rock on Mars between 10 and 12. (Carter *et al.* 2009).

2.2.2 Dielectric Loss

The ratio of ϵ' and ϵ'' is the loss tangent ($\tan\delta$) and is a measure of a materials efficiency at impeding the passage of electromagnetic waves:

$$\tan \delta_d = \frac{\epsilon''_r}{\epsilon'_r} \quad (2.4)$$

$\tan\delta$, like ϵ' , varies depending on the material. The $\tan\delta$ of air is at ~ 0 , water ice at ~ 0.0026 (Grima *et al.* 2009), and basaltic rocks on Mars between ~ 0.01 and ~ 0.03 (Carter *et al.* 2009). The $\tan\delta$ of water, unlike its ϵ' , increases sharply with frequency due to changes in ϵ'' . From the lowest frequencies to ~ 4 GHz, $\tan\delta$ rises from ~ 0 to ~ 0.2 , but can reach as high as ~ 2 at much higher frequencies (Lide *et al.* 1996).

2.3 Attenuation

Both ϵ' and $\tan\delta$ determine the the maximum depth that a signal can travel and then can return to the antenna and still be detectable above noise levels. The rate at which the electromagnetic radiation transmitting through the material is lost with units of nepers per unit meter is known as the attenuation rate (α), where a neper (Np) is a logarithmic unit of measurement for comparing power quantities. α is represented as (Boivin *et al.* 2018):

$$\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{\epsilon_r'}{2} (\sqrt{1 + \tan \delta_d} - 1)} \quad (2.5)$$

Where λ_0 is the center frequency of the radar. α in terms of Np/m can be represented in dB/meter by using the equation (Stillman & Olhoeft 2008):

$$\eta = 20 \log_{10}(e^\alpha) \quad (2.6)$$

2.4 Phyllosilicate Attenuation on Mars

H_2O molecules, being polarized, have a strong effect on incoming radiation, and the value of ϵ' is ~ 80 for frequencies up to ~ 4 GHz (Lide *et al.* 1996). Because of this, hydrated minerals, such as phyllosilicates, can have a much higher ϵ' than their density would imply. The imaginary component, ϵ'' , and thus the $\tan \delta$, is also heavily influenced by the presence of liquid water molecules. A study released by Stillman & Grimm (2011) cites this high water content in clays as the primary reason that radar is unable to transmit through phyllosilicate deposits on Mars. The dipole nature of water molecules within phyllosilicates negatively interact with the electrical part of incident electromagnetic waves, resulting in the material having a high $\tan \delta$, impeding their passage through the material. This high $\tan \delta$ should attenuate SHARAD signals beyond the instrument's noise floor of -24 dB with a maximum η of 0.27 dB/m, accounting for a maximum phyllosilicate thickness of 16 m for detectable signals.

2.4.1 Contradictions

However, an unpublished basal reflection map presented by Smith *et al.* 2019, had shown widespread subsurface detections over Aurorae Planum. The mapped reflections occur primarily in the western portion of the plateau. Smith et al.'s map is not clutter mitigated over Aurorae Planum, however, as we show through our clutter mitigation of the region, these basal reflections are wide spread over the western half of the plateau (Fig. 2.1). The process for how we conduct the clutter mitigation is described in Section 5.2. These

observations occur in phyllosilicate rich regions (Fig. 1.2), contrary to what is predicted by Stillman & Grimm (2011), setting up a problem that we aim to resolve here.

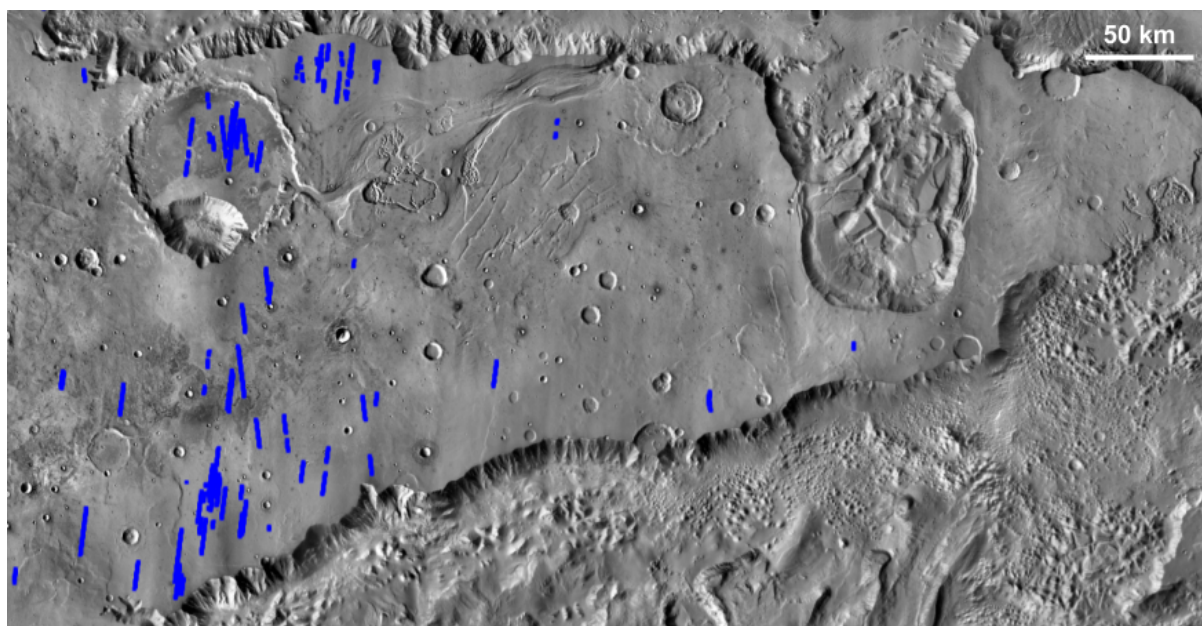


Fig. 2.1: SHARAD Observation Map

Map of detected basal reflections from SHARAD data. Each blue line represents a subsurface detection from radar data. This map has been mitigated of clutter. Basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

3 Research Hypothesis and Plan

In this study, we explore three potential explanations for these contradictory observations:

3.1 Hypothesis 1

Our first hypothesis is that the phyllosilicate deposits of these regions have lost some percentage of their adsorbed water. Significant enough water loss will lower the $\tan\delta$ of the material to a point where the radar signal can transmit through the surface, reflect from a deeper interface, and return with a detectable signal above noise. We propose that the mechanism of desiccation for these phyllosilicate deposits is related to water the retreat of the water table in the region, leaving the clays to desiccate through the late Hesperian and into the arid, near vacuum pressure environment of the Amazonian (El-Maarry *et al.* 2015). Such a desiccation mechanism would cause the attenuation rate to be lower than the 0.27 dB/m maximum predicted by Stillman and Grimm (2011).

3.2 Hypothesis 2

A secondary mechanism could be that the phyllosilicate deposits are thinner than expected, based on the time delay of the reflections measured by SHARAD. In this scenario, the phyllosilicates would be of a normal hydration state, more aligning with the work of Stillman & Grimm (2011). Either the phyllosilicate layers are thinner than SHARAD's vertical resolution, or the layer thicknesses are such that the attenuation rate of the material does not fully attenuate the radar signal. This would then require the reflections are caused by a subsequent interface below that of the phyllosilicates - thus creating a two layer model on top of the basement.

3.3 Hypothesis 3

The third hypothesis is a possible combination of the first two hypotheses. This would be the case if the phyllosilicate layers have both experienced significant desiccation, and are thinner than previously expected. This raises the bar for the maximum thickness permitted and level of desiccation that the clays have experienced as it balances the time the signal travels through the medium with the loss that the signal experiences as it travels.

3.4 Morella Crater Outflow Event Hypothesis

In order to test our Hypotheses, we consider the presence of polygonal fractures located around Aurorae Planum. El-Maarry et al. (2015) compared polygonal fractures in Mawrth Vallis, similar to those of Aurorae Planum, to Earth analog dried lake beds. The study found desiccation due to water table retreat as a primary formation mechanism. It is possible then, that a similar process has occurred at Aurorae Planum.

Particularly, the flooding event that is responsible for carving Elaver Vallis would have left water pooled in the crater, in the southern basin, and potentially on the northern flatlands. These pooled bodies of water would evaporate slowly after the flooding ceases, leaving a perfect environment for low temperature chemical alteration of the sediments, generating new phyllosilicates. With no readily available source of water, these pooled lakes would eventually evaporate. The retreat of the water table through evaporation would cause the formation of polygonal fractures as the clays desiccate to the open atmosphere. This desiccation should serve to lower the η to a point where SHARAD radar can transmit and reflect back with minimal loss.

3.5 Proposed Research

We test these hypotheses in five steps by pairing lab based dielectric experiments with remote sensing analysis of and around the SHARAD observations.

We first perform dielectric measurements on terrestrial analog materials of similar composition to the Fe/Mg and Al phyllosilicates located around Ganges Chasma, such as Ca-Montmorillonite. The samples are desiccated to varying degrees in order to constrain the dielectric properties and water mass loss percentage of the samples with what is observed at Aurorae Planum in later steps.

In the next step we analyse SHARAD data over Aurorae Planum to map true basal reflections. After mapping the reflections we measure the time delays for each detection. The resultant spatial map is used in the next section to conduct a visible and spectral data analysis of Aurorae Planum. The locations of the basal reflections are cross referenced with HiRISE and CRISM data in order to confirm a spatial correlation of the region with phyllosilicates. Identifying a correlation between the location of the basal reflections and the presence of polygonal fracturing and the presence of phyllosilicates will support desiccation as a possible mechanism, supporting Hypothesis 1 (Section 3.1). Additionally, the dimensions of the polygons are measured in order to identify a thickness of the clay layers. This thickness measurement directly correlates to the validity of our second hypothesis (Section 3.2).

The fourth step is to compare the data from the lab based experiments (Step 1) to the data from the remote sensing analysis (Steps 2 and 3). We calculate the depth of the observed basal reflections for a spectrum of possible phyllosilicate layer permittivities followed by calculating the maximum possible transmission depth for a phyllosilicate layer based off of our lab based measurements. Comparing the observed depths to the calculated critical depths will show whether reasonable desiccation is enough to account for the reflection depths that are observed. This will directly correlate to Hypothesis 1 and 2 (Sections 3.1 and 3.2).

As a supplemental step, we also conduct lab experiments with phyllosilicate saturation. We monitor the desiccation process of a phyllosilicate sample that has been thoroughly hydrated. The resulting polygonal patterns are analysed and compared to the polygons observed at Aurorae Planum in order to further support desiccation as a dehydration mechanism.

4 Step 1: Dielectric Laboratory Measurements

The first step of our research is to determine the dielectric properties of analogue phyllosilicates to those that are located around Aurorae Planum, at varying levels of hydration. To do this, we use methods similar to those of Boivin *et al.* 2018.

4.1 Equipment Setup

4.1.1 Vector Network Analyser

As light enters a new medium, its velocity slows according to the medium's dielectric properties. In addition to this, the light, at the meeting of the interface, will either transmit through, reflect from the interface, or will have its energy absorbed. In a laboratory environment, the extent of which of these phenomena occur, known as the scattering parameters (S-Parameters) can be measured using a two port Vector Network Analyser (VNA).

A two port VNA generates an electromagnetic signal at ramping frequencies. Both ports of the VNA are capable of transmitting and receiving this generated signal. During a measurement cycle, there are eight values that are recorded. First, the signal is transmitted through port 1. The transmitted signal from port 1 to port 2 (S_{12}) is measured along with the signal's phase. The reflected signal from port 1 is also recorded back at port 1 (S_{11}) along with the reflected phase. Second, the process is repeated, this time transmitting through port 2. The transmitted signal to port 1 and its phase is recorded (S_{21}) as well as the reflected signal back to port 2 (S_{22}) and its phase.

Theoretically, in a perfect system, S_{12} and S_{21} should be equivalent, as they rely purely on the inherent transmission and reflection coefficients of the medium. Likewise, S_{11} and S_{22} should also be equivalent with the same reasoning. These S-parameters are calculated such that:

$$S_{11} = S_{22} = \frac{\Gamma(1 - T^2)}{1 - \Gamma^2 T^2} \quad (4.1)$$

$$S_{12} = S_{21} = \frac{T(1 - \Gamma^2)}{1 - \Gamma^2 T^2} \quad (4.2)$$

Where Γ is the reflection coefficient and T is the transmission coefficient. Γ and T are inherent properties to a material. They describe the fractional amplitude of the incident wave that respectively reflects from or transmits through the interface of the dielectric medium. These coefficients are represented such that:

$$\Gamma^2 + T^2 = 1 \quad (4.3)$$

$$\Gamma = \frac{\gamma_0 \mu_r^* - \gamma}{\gamma_0 \mu_r^* + \gamma} \quad (4.4)$$

$$T = \exp(-\gamma d) \quad (4.5)$$

Where μ_r^* is the complex magnetic permittivity, and d is the length of the airline. For nonmagnetic materials, such as phyllosilicates, μ_r^* is negligibly close to 1. γ_0 is the propagation constant of an empty airline and γ is the propagation constant of a filled airline so that:

$$\gamma_0 = i \frac{2\pi}{\lambda_0} \sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \quad (4.6)$$

$$\gamma = i \frac{2\pi}{\lambda_0} \sqrt{\epsilon_r^* \mu_r^* - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \quad (4.7)$$

Where λ_0 is the free space wavelength, λ_c is the cutoff wavelength of the waveguide (where $\lambda_c \xrightarrow{\infty}$ for a coaxial waveguide) and ϵ_r^* is the material's complex permittivity. (Weir 1974, Baker-Jarvis *et al.* 1993, Boughriet 1997, Boivin *et al.* 2018).

Powdered samples, such as the phyllosilicates used in this study, will not provide homogeneity due to remnant air gaps between grains, and therefore will yield some variation between the values of S_{11} and S_{22} , and between S_{12} and S_{21} .

The specific VNA that we use in this study is the Agilent E5071C two port VNA (Fig. 4.1). This VNA is capable of sweeping between 300 kHz - 12 GHz with a source power range of -55 to +10 dBm, where dBm is a unit of power in regards to decibels with reference to one milliwatt. It features two N-Type female ports for attaching active and passive cables. N-Type connectors are pin type radio frequency connectors used typically for connecting coaxial cables. Active cables draw power from the system, while passive cables do not. The VNA runs WindowsXP for data storage and features an LCD touch screen for ease of use.

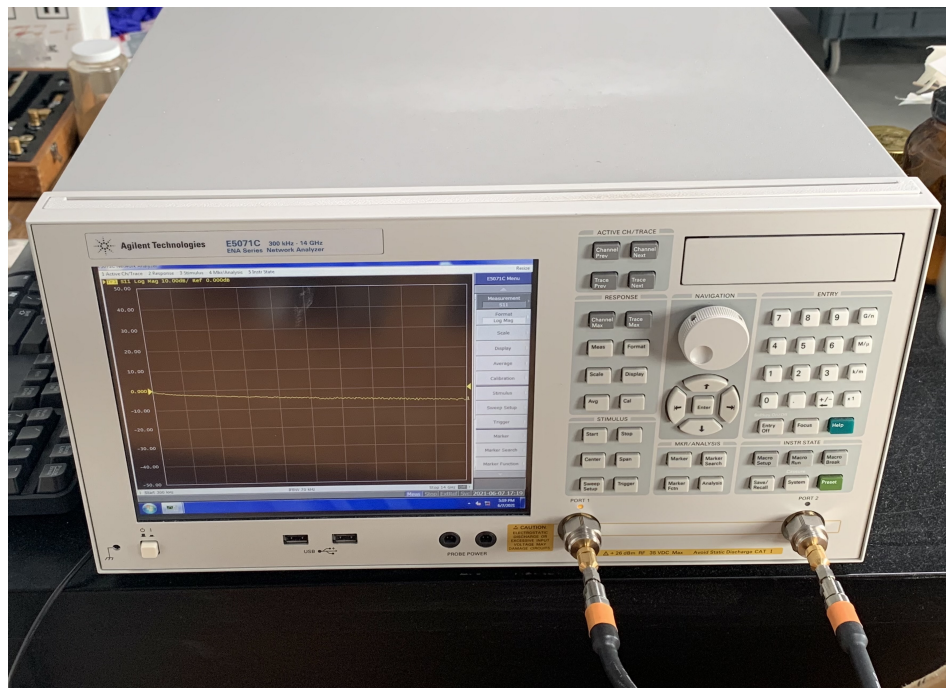


Fig. 4.1: Agilent E5071C ENA series Vector Network Analyzer
The VNA used in this study.

4.1.2 Coaxial Airline

We use a coaxial airline setup to conduct the S-parameter measurements on powdered samples. The airline is a hollow conductive tube with a smooth interior lining that holds a sample within it. In the center of the airline is a center conductor rod with two spring loaded fastening pins at either end to hold the rod in place with the connectors. The airline

is threaded on either end to secure it to the cable connectors that attach to the VNA.

For this study we use the General Radio GR900-LZ15 15 cm length coaxial airline (Fig. 4.2). 15 cm provides an acceptable trade-off between sample size and measurement uncertainty (Sotodeh 2014). The airline has a diameter of 14 mm, which is an ideal size for sample packing, as smaller diameters prove to be more difficult to ensure an even packing (Sotodeh 2014). Additionally, the airline has a 50- Ω impedance, which matches the impedance of the VNA. It is operational from a frequency range of direct current to 8.5 GHz that falls within the threshold of the range of the VNA mentioned in the previous section.

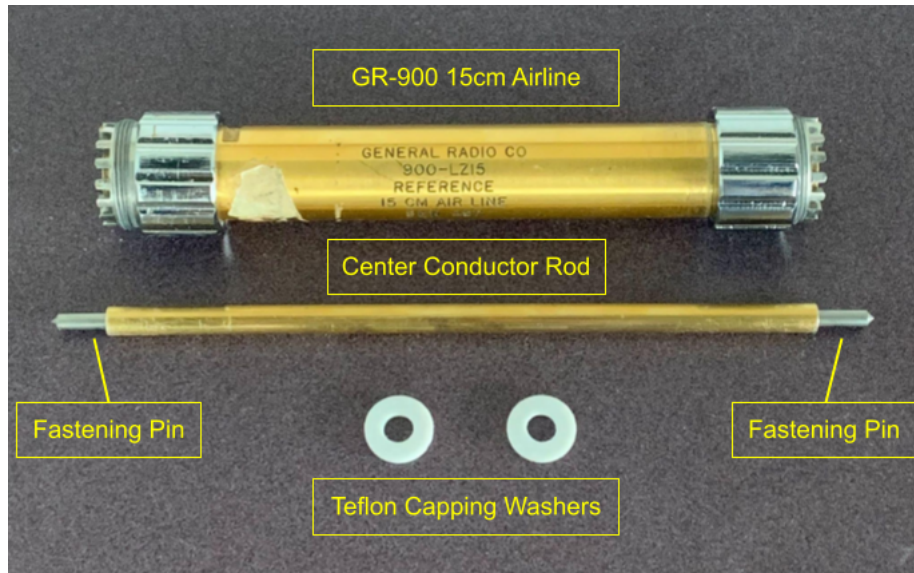


Fig. 4.2: General Radio Coaxial Airline Setup

The coaxial airline setup used in this study, complete with fastening pins, center conductor and teflon capping washers, discussed in Section 4.1.8

4.1.3 Calibration Standards

The instrument calibration standards used in this study are from the GR-900 14 mm 50- Ω impedance set. We use a Short and a Load standard (Fig. 4.3). Like the airline, they are rated for frequencies from direct current to 8.5 GHz. Both standards are threaded in order to connect to the VNA.



Fig. 4.3: GR-900 Short and Load Calibration Standards

The calibration standards used in this study. They are attached to the connectors discussed in Section 4.1.4 to conduct the calibration measurements.

4.1.4 Adapters and Cables

We use four Maury Microwave SC-35MM-36-TV microwave/RF cables (Fig. 4.4). The cables are four feet in length and boast a maximum flexure of $\pm 2^\circ$. Additionally they are abrasion, crush and fire resistant, with a maximum operating frequency of 18 GHz (Microwave 2013) Two connect directly to port one and two of the VNA with 3.5 mm male to male connectors, with the other ends connected to a custom built vacuum chamber later discussed in Section 4.1.9. The remaining two cables connect from the interior of the chamber to the airline.

The cables are connected to the airline with General Radio GR900-QMMJ 3.5 to 14 mm adapters (Fig. 4.4). Similarly to the airline and calibration standards, these connectors have a frequency range of direct current to 8.5 GHz and a matched impedance of 50- Ω .

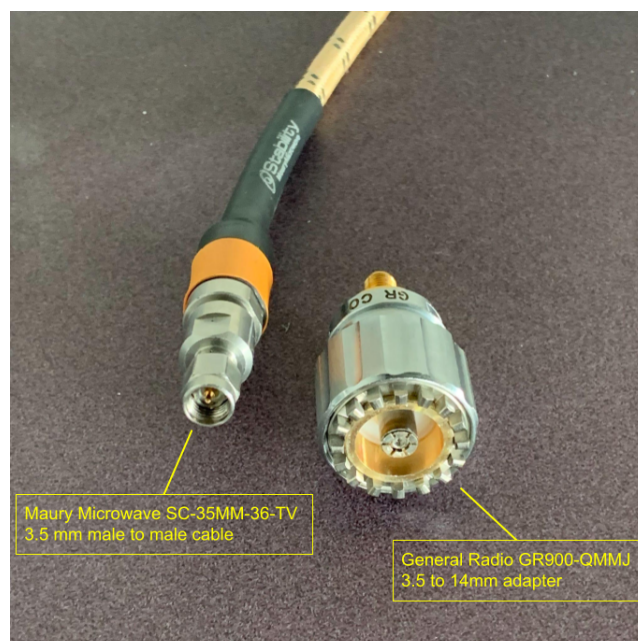


Fig. 4.4: Maury Microwave SC-35MM-36-TV Cable connector and General Radio GR900-QMMJ 3.5 to 14 mm adapter

The cable and connector used to carry the generated signals from the VNA to the attached sample.

4.1.5 Kiln

To dehydrate our samples, we elect to bake them using a cone firing kiln. We use a Paragon SC-3 Digital Automatic kiln (Fig. 4.5). This kiln comes equipped with a Sentry Xpress 3.0 micro processor that enables the control of time and temperature. It is capable of programmable cone-fire and ramp-hold procedures up to 2000 °C. The procedures can be run for any desired time frame.



Fig. 4.5: Paragon SC-3 Digital Automatic Kiln

The kiln used to bake samples in order to simulate water loss in the Martian environment.

4.1.6 Deionizing Balance

The nature of our experiments requires that we have accurate measurements of the mass of our samples, making a precise scale an imperative instrument. In addition, it's important to remove excess charges from powdered samples, since static electricity can cause troubles when packing a powdered sample. While the static electricity does not affect the dielectric measurements, it does cause small powdered particles to stick to the funnel and airline walls. Removing the static electricity allows for more even packing of the sample. Therefore, we utilize a Sartorius MSA524P-100-DI Cubis Precision Balance with ionizing capabilities (Fig. 4.6). The balance has an accuracy of $\pm 0.00005\text{g}$ which is more than enough for the purposes of this study. The ionizer is used to neutralize static electricity before and after packing is completed.

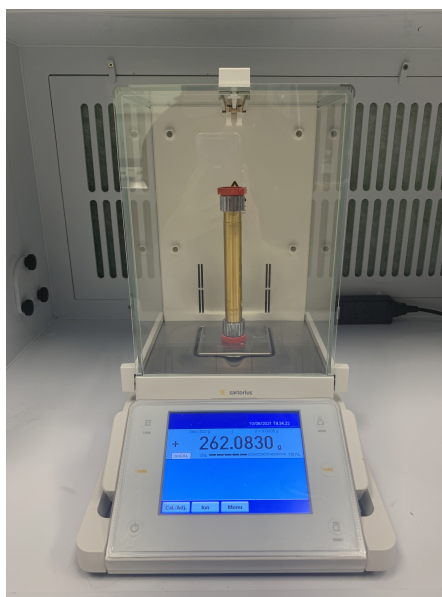


Fig. 4.6: Sartorius MSA524P-100-DI Cubis Precision Balance

The precision balance used to measure the mass of the samples and the airline prior to each dielectric measurement.

4.1.7 Custom Funnel and Sieve Shaker

To streamline the sample packing process, we utilize a custom funnel attached to a Gilson Performer III SS-3 sieve shaker (Fig. 4.7). To ensure an even distribution of the sample in packing, the sieve shaker is run in prolonged bursts. The funnel is attached to the sieve shaker via two threaded rods and held in place with four wing nuts, two below and two above. We ensure that the funnel must be balanced to ensure a smooth packing, otherwise

the airline will be filled at an angle, increasing chance for air gaps. The funnel connects to the airline with a 14 mm threaded connector, and the center conductor rod is held in place by a centering rod.

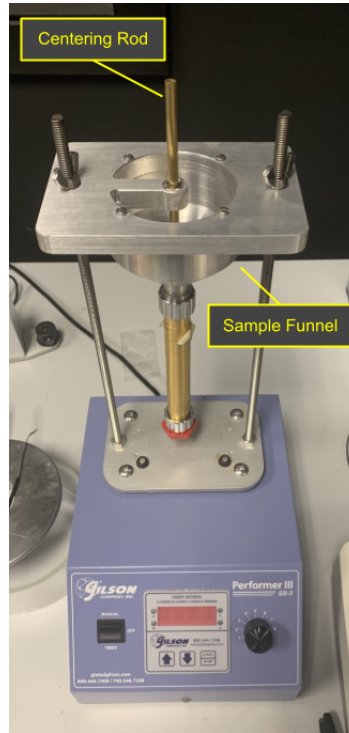


Fig. 4.7: Custom funnel attachment to Gilson Performer III SS-3 sieve Shaker

The funnel, sieve shaker setup used in this experiment. The funnel is designed to streamline the filling process with ease of packing.

4.1.8 Teflon® Washers

When measuring finely powdered materials, such as clay powders, the grains have a tendency to slip in between the teeth of the connectors. To mitigate this occurrence, using a cap to fit tightly into the top of the airline and tightly around the center conductor is advised. For this study, we use custom machined Teflon® washers that are 1.7 mm thick (Fig. 4.2 and Fig. 4.8). They have an outer diameter of 9/16" (~14.28 mm) and an inner diameter of 15/64" (~5.95 mm). These measurements are slightly larger than the inner diameter of the airline and the outer diameter of the rod in order to ensure an airtight fit. We use Teflon® because the material has a constant ϵ' of 2.1 at all frequencies that can easily be corrected for in our analysis.



Fig. 4.8: GR-900 Coaxial Airline with Teflon Washer Cap

Top view of the coaxial airline, highlighting the way in which the center conductor and teflon washer fits into place. The washer is designed to fit snugly minimizing air gaps as much as possible.

4.1.9 Vacuum Chamber

To bring the airline sample down to Mars pressure for measurement, we use a customized vacuum chamber (Fig. 4.9). This chamber is equipped with two flange ports with 3.5 mm connectors. These connectors allow the both cables to connect through to the airline while still maintaining a vacuum. In the center of the chamber are two rods that are 15 cm apart, each with clamps at the top. These clamps are to hold the airline in place during measurement. The vacuum chamber is capable of holding a vacuum down to ~ 5 Torr. The chamber is limited to ~ 5 Torr and must have the pump running for the duration of the experiment due to an untraceable air leak.

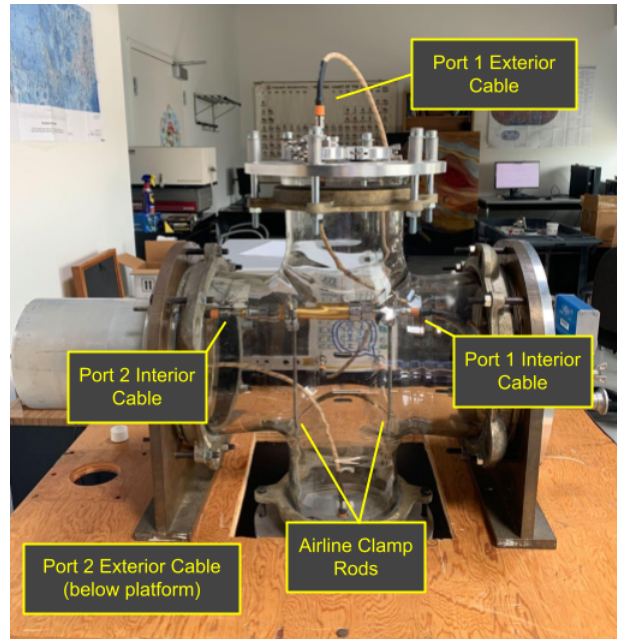


Fig. 4.9: Vacuum Chamber Measurement Setup

The vacuum chamber used to measure the dielectric properties of the sample at Mars pressures. The chamber is designed specifically for these kinds of experiments, featuring cable ports to transfer from the VNA to the interior of the chamber.

4.2 Measurement Procedure

4.2.1 METAS VNA Tools II

We control the VNA with the use of METAS VNA Tools II, instead of the default software. This allows the advantage of advanced calibration techniques, uncertainty calculation and propagation, and a log of the calibration and measurements, allowing repeatability and traceability. Most importantly, it allows quick and easy visualization of the measured S-Parameters after measurement (Boivin *et al.* 2018) (Fig. 4.10).

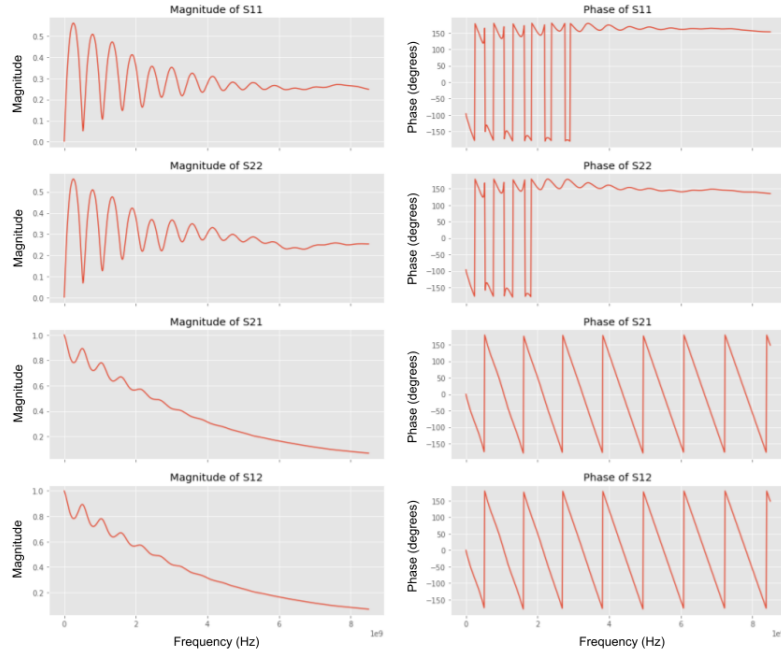


Fig. 4.10: S-parameter Plot of JSC Mars-1 Soil Simulant

This figure is representative of example data, and not related to this thesis work in any way except for validation. The "Magnitude" of each S-parameter refers to the decimal percent between 0 and 1 of the signal that was respectively transmitted or reflected to the measuring port at that particular frequency. The Phases are representative of which phase the electromagnetic wave arrives at the detector, either transmitted or reflected, respectively.

4.2.2 VNA Settings

The VNA is set with the following settings for each experiment:

- Frequency Start: 300 kHz
- Frequency Stop: 1 GHz
- Power: -10 dBm
- Intermediate Frequency Bandwidth: 10 Hz
- Averaging Factor: 5
- Points: 801

The frequency start and stop are respectively the frequency that the VNA begins the sweep at and the frequency that the VNA ends its sweep at. We select this specific range to optimize our data resolution at SHARAD's operational frequency of 20 MHz, and to prepare for proposed radar instruments at Mars that will have operating center frequencies of ~ 1 GHz. The power is the absolute power sent through the system in terms of dB with reference to one milliwatt. We use a value of -10 dBm to avoid receiver compres-

sion (Sotodeh 2014). The Intermediate Frequency Bandwidth is the lower intermediate frequency that the received signal is converted to during the averaging process. Setting it to 10 Hz reduces the noise floor as much as possible (Sotodeh 2014). The averaging factor is how many sweeps are measured and then averaged together. The points is the amount of data points measured throughout the sweep. The points are measured logarithmically over the frequency range, therefore measuring more points allows for finer resolution at lower frequencies.

4.2.3 Calibration

The calibration method we use in our experiments is a Through-Reflect-Match (TRM) calibration scheme. TRM calibration schemes are highly accurate for broadband measurements (Boivin *et al.* 2018). The through portion of the calibration is meant to model a zero length airline, accounting for noise experienced in S_{12} and S_{21} measurements (Fig. 4.11 a.). The reflect portion models a symmetrical reflecting load where the impedance is unknown. This term accounts for noise that occurs within the connectors and cables in the S_{11} and S_{22} measurements (Fig. 4.11 b.). The match term simulates an infinite airline by creating an open circuit, which will account for the internal noise of the instrument (Pulido-Gaytán *et al.* 2015) (Fig. 4.11 c.). In addition to these three calibration measurements, we also measure the Switch Terms of the VNA instrument. The switch terms are the reflection coefficients at the port of termination for each throughput configuration (Marks 1997).

Through the calibration process, we conduct six different measurements. We begin by conducting the through measurement by connecting the two GR900-QMMJ connectors to create a throughput as the VNA measures the S_{11} , S_{12} , and then S_{22} and S_{21} . After that measurement step is completed, the cables are left in place and the Switch terms are measured. The next calibration step is to disconnect the two connectors, and attach the short standard to port one and the match standard to port two. Measurement of S_{11} is then conducted, and immediately following, S_{22} is measured. Then, the reflect and load standards are swapped and the previous measurement step is repeated.

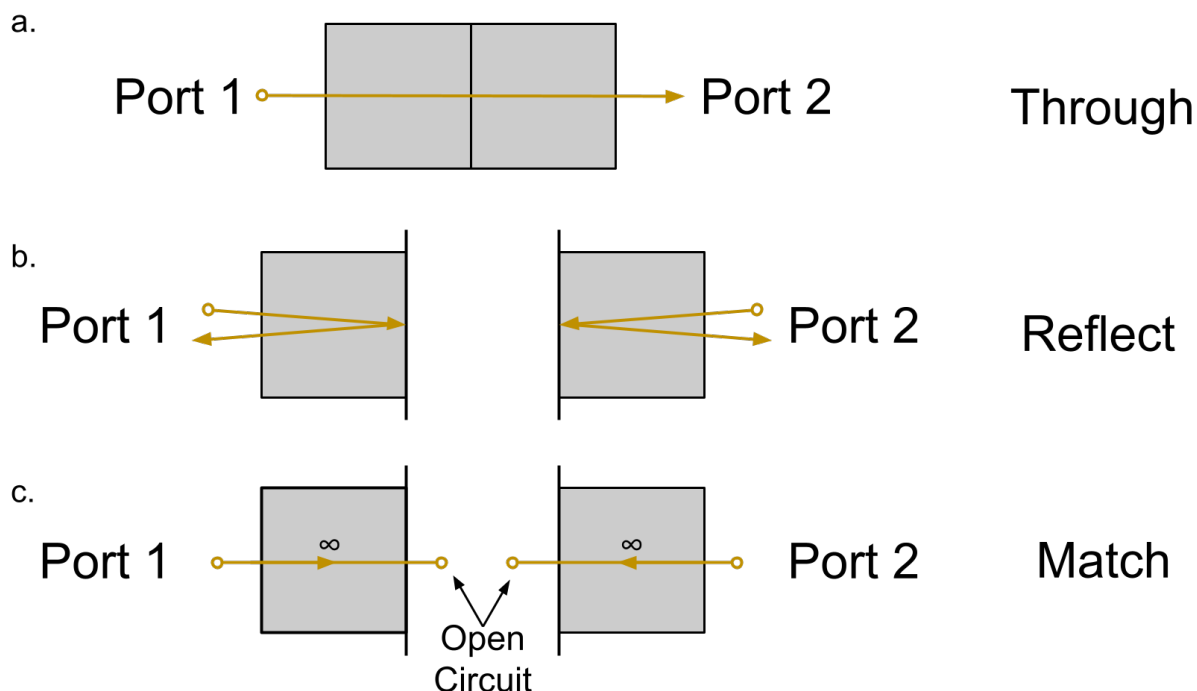


Fig. 4.11: TRM Calibration Diagrams

Sketches of the function of each part of a TRM calibration. **a.** The through measurement connects the two cables directly and transmits the signal from one port to another. **b.** The reflect measurement transmits a signal from one port to the reflect standard which theoretically perfectly reflects the signal back to the origin port. **c.** The match measurement transmits a signal from one port to the load standard which acts as an open circuit, theoretically absorbing all energy with no reflection.

4.2.4 Measurement Preparation

The dried samples are prepared first by baking them at a set temperature for 24 hours. This will simulate the desiccation over time experienced in the Martian environment but at a pace that we can complete in a laboratory setting. We are careful to not bake the sample at temperatures any greater than 250 °C, as baking a sample of stx-1b at 300 °C or above results in irreversible dehydration, through the breakup of OH molecules, as we learned from experience through our measurements. This was realized after baking a sample at 800 °C and noticing a distinct color change, signifying a change in chemical composition. The mass of the sample is measured before and after baking to observe the percentage of water mass lost throughout the baking process. This value is later used to calculate the percentage of the water lost in the original mass of the sample. In addition we measure the mass of the airline before and after packing in order to calculate the bulk density of the sample since volume is known and constant between measurements. Immediately

after measuring the masses, the sample is packed into the airline via the custom funnel attached to the sieve shaker. Through the packing process, one or two scoops of sample are added at a time. After each couple of scoops of added sample, the airline is removed from the funnel in order to use a packing rod to pack down the sample. This process ensures a tightly packed sample so that air gaps between grains are minimized. After the airline is fully filled, the airline is then capped with the Teflon® washers. The control measurement is packed into the airline following the same process. It is packed into the airline directly from the sample container with no prior preparation or alteration. This allows measurements at an ambient hydration state to serve as a baseline for our dried measurements.

4.2.5 Measurement Process

After calibrations and sample packing is completed, the airline is attached to both cables and placed inside of the vacuum chamber. The vacuum chamber is then pumped down to ~ 5 Torr, which is close to Mars pressures. Once the vacuum is stabilized, the through measurements are conducted, as detailed in Section 4.1.1.

4.3 Error Analysis

Uncertainties in the measurements due to cable instability, inhomogeneity in the airline packing, instrument noise and drift, etc. are calculated using methods from Boivin *et al.* 2018 that takes into account both Type A and Type B uncertainty.

Type A Uncertainty is uncertainty encountered in the statistical analysis of and propagation through the dielectric calculations where (Boivin *et al.* 2018):

$$\text{Type A uncertainty for } \epsilon'_r = \text{Max}(\sigma_{\max}^{\epsilon'_r} |\epsilon'_r[S_{11}, S_{21}] - \epsilon'_r[S_{22}, S_{12}]|) \quad (4.8)$$

$$\text{Type A uncertainty for } \tan\delta = \text{Max}(\sigma_{\max}^{\tan\delta} |\tan\delta[S_{11}, S_{21}] - \tan\delta[S_{22}, S_{12}]|) \quad (4.9)$$

Type B uncertainty is uncertainty observed by non-statistical analysis means. It accounts for uncertainties inherent within the measurement system that are not propagated through the calculations like Type A, such as the internal noise of the VNA, VNA drift, VNA linearity, VNA Calibration drift, connector repeatability, and cable stability. METAS VNA Tools II is able to track and calculate all of these uncertainties to be added to the propagated Type A uncertainty.

The total uncertainty for types A and B is (Boivin *et al.* 2018):

$$\text{Total uncertainty} = \sqrt{(\text{Type A uncertainty})^2 + (\text{Type B uncertainty})^2} \quad (4.10)$$

Uncertainty in these measurements due to the equipment used was the subject of a M.Sc. thesis and an additional Ph.D. thesis on this same equipment (Sotodeh 2014, Boivin *et al.* 2018) and not discussed further here.

4.4 Permittivity Calculations

The output data from the VNA measurements is processed using a custom python code, permittivitycalc (Boivin & Hickson 2020). Permittivitycalc extracts the s parameters and solves for ϵ' , ϵ'' and $\tan\delta$ using the New Non-Iterative Method for low loss materials (Boughriet 1997), which is based off of the Nicholson Ross Weir Method (Nicolson & Ross 1970, Weir 1974. The Non-Iterative Method utilizes the relationships depicted in Section 4.1.1 to calculate ϵ_r^* , assuming a nonmagnetic material, where $\mu_r^* = 1$ Boughriet 1997:

$$\epsilon_r^* = \frac{\lambda_{0g}^2}{\Lambda^2} \quad (4.11)$$

Where λ_{0g} represents the free space wavelength parameter, such that:

$$\lambda_{0g} = \frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \quad (4.12)$$

And $\frac{1}{\Lambda^2}$ is:

$$\frac{1}{\Lambda^2} = \left[\frac{i}{2\pi d} \ln(T) \right]^2 \quad (4.13)$$

4.5 Bulk Density Correction

Due to the powdered nature of dried clays, there is an expectant porosity in our samples. These air gaps between grains must be corrected for in order to receive accurate data. There are a number of mixing equations used to normalize this (Hickson *et al.* 2017). The mixing equation used in this study is the Lichtenecker Mixing Formula (Sihvola & Burns 1999, Hickson *et al.* 2017):

$$\epsilon'_r = \epsilon'_{r,e}{}^{1-f} \epsilon'_{r,i}{}^f \quad (4.14)$$

Where $\epsilon'_{r,e}$ and $\epsilon'_{r,i}$ are the real parts of the permittivity for the fluid and the particle, respectively. In this case, the fluid is the vacuum space between grains, where $\epsilon \approx 1$, and the particle is the clay powders. f is the volume fraction of the solution, calculated from the bulk density of the sample:

$$f = \frac{\rho_{bulk}}{\rho_{particle}} \quad (4.15)$$

Through our dielectric measurements, permittivitycalc solves for $\epsilon'_{r,i}$ to normalize the measured ϵ' .

4.6 Measurement Validation Steps

In order to test the validity of our measurement process and the condition of the measurement instruments and components, we conducted experiments on two test materials: Rexolite and JSC MARS-1 Soil Simulant. These measurements are conducted with the intention of replicating the results of Boivin *et al.* 2018 to prove that we are capable of achieving accurate results. Boivin *et al.* 2018 utilizes the same setup and measurement technique for their measurements as we describe in 4.2.2, except for the stop frequency at 8.5GHz and the points set to 601.

4.6.1 Rexolite Standard

Rexolite acts as an excellent standard for measurement, as it has a very stable ϵ' of 2.53 and $\tan\delta$ across a broad frequency range. We use a custom machined Rexolite rod to fit within the 14 mm airline (Fig. 4.12).

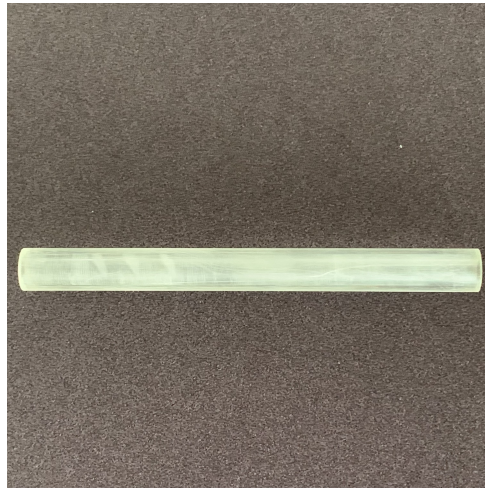


Fig. 4.12: Rexolite Sample Rod

The Rexolite sample used to conduct our validation tests on the Airline. This is the same rod used by Boivin *et al.* 2018.

Comparing our results (Fig. 4.13) we find good agreement between our data and Boivin's data. On average, our measurements of ϵ' has a discrepancy of ~ 0.09 , or close to 0.1. This discrepancy explained by a slight air gap in our measurements that could not be corrected for. Despite this discrepancy, a permittivity difference of 0.1 is not consequential to the results of this study. The $\tan\delta$ aligns better than the ϵ' , with an average point discrepancy

of ~ 0.0003 , which is well within an acceptable margin of error. The error bars may appear large, however it should be noted that this material has such an incredibly low loss that instrumental noise signals appear far larger than the magnitude of signal that is lost, yielding high degrees of error, relatively.

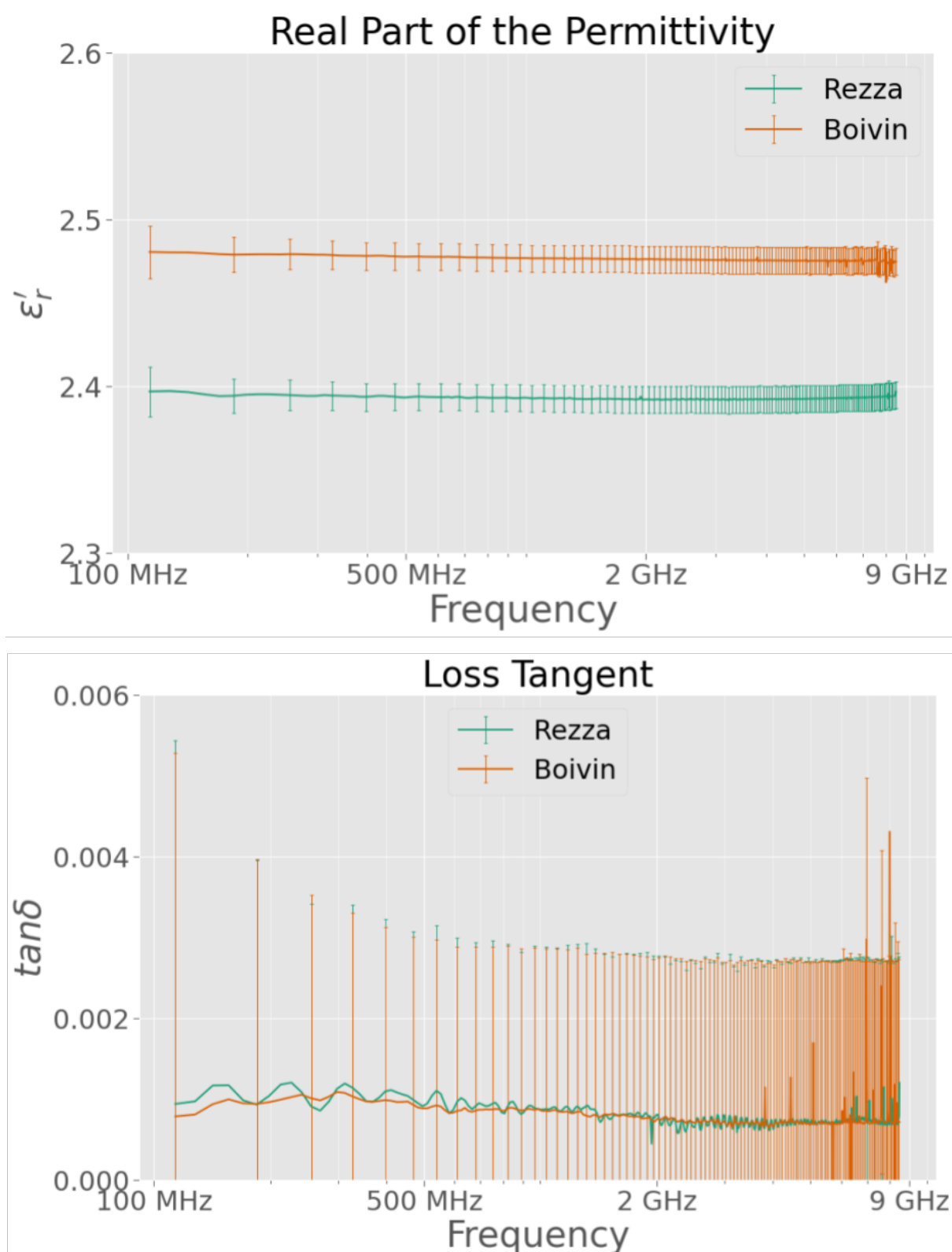


Fig. 4.13: Rexolite Dielectric Measurement Comparison

Rexolite ϵ' and $\tan\delta$ measurement comparison between Rezza and Boivin, conducted from 300 kHz to 8.5 GHz. The frequency axis is presented logarithmically to reflect the way the density of measurement points increases at higher frequencies.

4.6.2 JSC MARS-1 Soil Simulant

JSC MARS-1 Soil Simulant is an analog model of the soil of Mars (Fig. 4.14). The soil simulant consists primarily of volcanic ash from Pu'u Nene We, a cinder cone in Hawaii. It is a highly ferric and magnetic material (Golden *et al.* 1998). We prepare this sample by baking it for 24 hours to remove its moisture, and prepared it as detailed in Section 4.2. This measurement served to develop and validate our baking procedures, as well as to serve as continued validation for our measurement procedures.



Fig. 4.14: JSC MARS-1 Soil Simulant
Sample of JSC MARS-1 Soil Simulant.

Comparing our data to the measurements of Boivin (Fig. 4.15), we again find good correlation with our data. Our sample measurement of ϵ' is within an average of ~ 0.05 of Boivin's sample. The $\tan\delta$ between the two is also ~ 0.05 . It is clear that at lower frequencies, the ϵ' values are better matched, and slowly begin to deviate. The same is noticed for the $\tan\theta$ values. We attribute these discrepancies to differences in moisture content of the samples. This discrepancy only becomes apparent at frequencies above 500 MHz. Otherwise, the validity of our measurements and the state of the instruments is demonstrated.

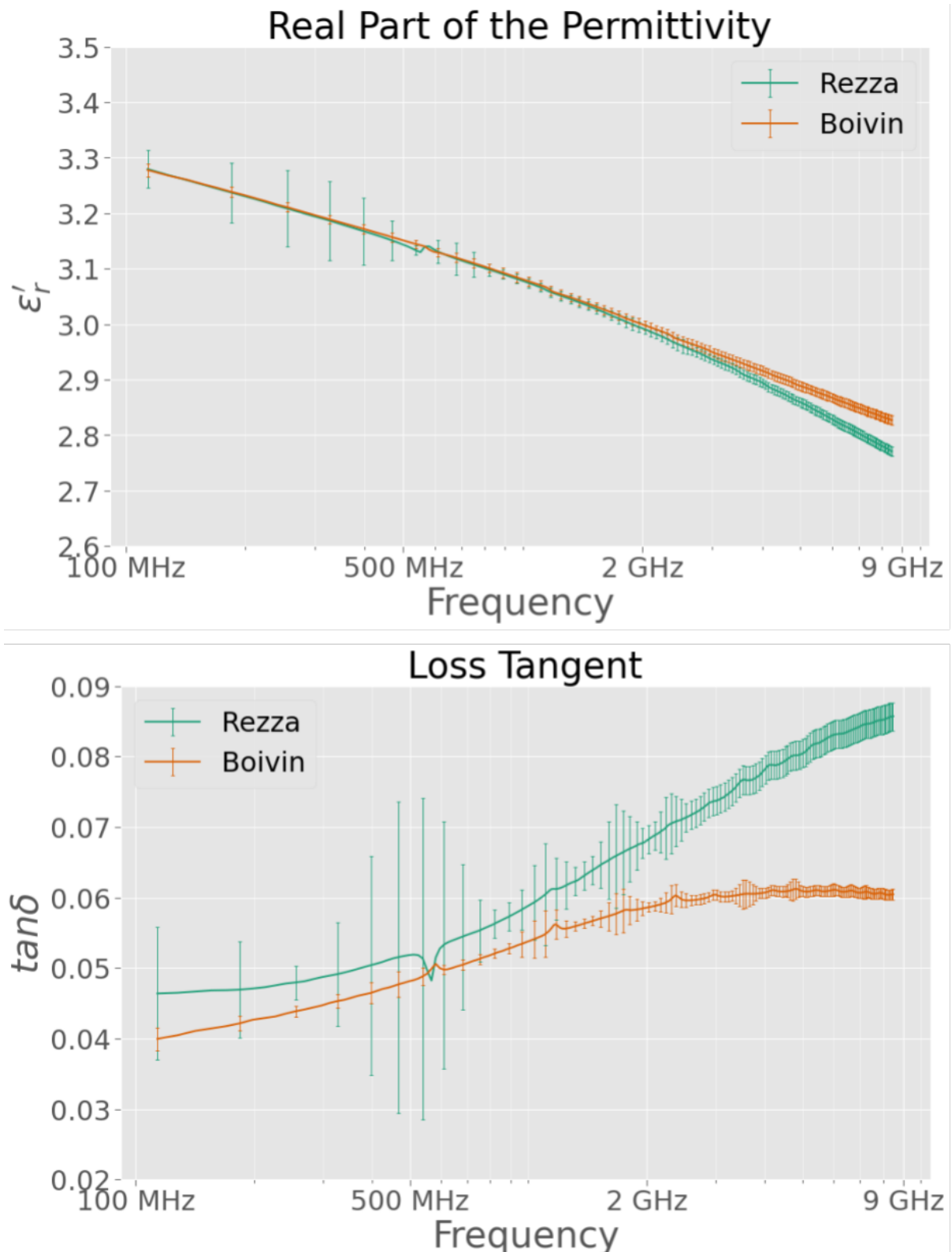


Fig. 4.15: JSC MARS-1 Dielectric Measurement Comparison

JSC MARS-1 ϵ' and $\tan \delta$ measurement comparison between Rezza and Boivin, conducted from 300 kHz to 8.5 GHz. The frequency axis, like the Rexolite plot, and all following dielectric plots like this, is presented logarithmically to reflect the way the density of measurement points increases at higher frequencies.

5 Step 2: SHARAD Data Analysis

Step 2 of this project is to conduct an analysis on the SHARAD tracks of Aurorae Planum. The first part of this analysis is to identify and map bright reflections below the surface. We then remove any potential off nadir reflections, or side-lobe artifacts from our mapped reflections. Once the tracks have been clutter mitigated, we record the time delay of each true reflection. This process will later allow us to calculate the depths of the reflections, as described in Section 7.

5.1 SHARAD Mapping

To map the reflections, we use Seisware, a commercially available geoscience software package that allows the analysis of radar data and mapping of basal reflections over a basemap. In the mapping process, we are careful to not map side lobes, which are reflections that follow the path of the surface at a constant time delay from the surface of 250 ns. They are artifacts caused by the processing of a chirped pulse with convolution and must be marked as artifacts when analyzing radar data. We ensure to check for this constant depth during our clutter mitigation process, discussed in the next section.

5.2 Clutter Mitigation

As SHARAD orbits at an altitude of ~ 300 km, signals may return to the antenna from any direction due to atmospheric scattering. Scattered signals have the potential to reflect from topography outside of the target area. Those reflections may return to the receiver generating an artifact that is not true to the target region at that specific distance or time-delay. These artifacts may appear either above or below the true surface, depending on the time it takes to reach the receiver due to its angle of travel. These artifacts are regarded as "clutter" and need to be accounted for.

While you cannot remove the clutter from the radargrams, you can account for it by

comparing the radargrams to simulated cluttergrams (Fig. 5.1) (Choudhary *et al.* 2016). Cluttergrams are simulations of radar clutter generated from 3D elevation model data from the Mars Laser Altimeter (MOLA). Comparing the true observations side by side with the cluttergrams allows us to easily discern between true reflections and clutter artifacts in the data. The methods we follow for the clutter mitigation process are the same as used by Putzig *et al.* (2009) and Smith & Holt (2015).

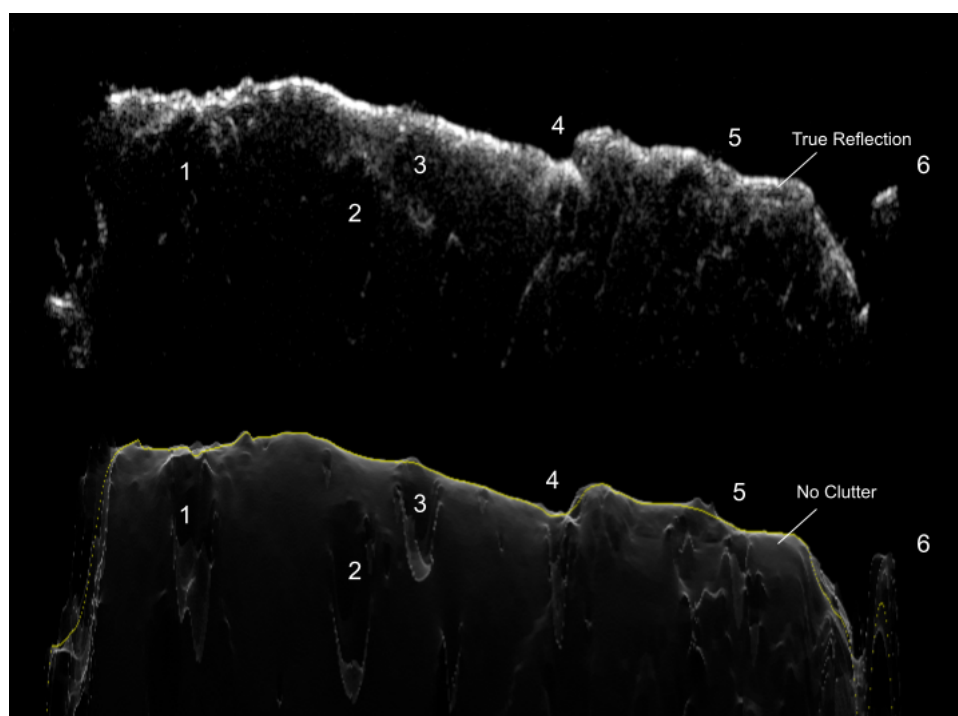


Fig. 5.1: SHARAD Track 4518601 Across Aurorae Planum Compared to its Simulated Clutter Model

Labelled are several examples of clutter that appear within the radargram. Each example matches up to an artifact generated in the simulated clutter model. Some clutter may appear below the surface, such as with clutter examples 1-3, and others appear above the surface, such as with examples 4-6. All Radargrams and clutter simulation data from the CO-SHARPS processing boutique, courtesy of the SHARAD Team at LPI.

Each track subject to clutter mitigation is opened in an imaging processing software with the clutter simulation overlain the SHARAD data. The opacity of the simulation layer is adjusted to identify if there is a clear match between the two. If the bright reflection matches up to an artifact on the cluttergram, then it is deemed clutter and removed from the mapping in Seisware. If it is not clear, or does not match, then the observation is put under further scrutiny with the use of an echogram, another simulated MOLA product that outlines the origin of off-nadir clutter along-track (Choudhary *et al.* 2016)(Fig. 5.2). The echogram is used along with a THEMIS image of the region (Fig. 5.3) in order to

determine if there is any slight topography variations along track that can explain the detection. If none of these tests can explain the bright reflection, then the reflection is deemed to be a true subsurface layer reflection.

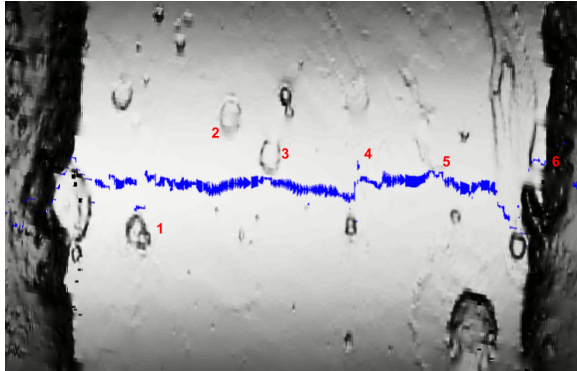


Fig. 5.2: Echo Model of SHARAD Track 4518601

5.2: The echogram models the radar echo received by SHARAD from off nadir topography. The numbers referenced in this map align with the clutter observed in Fig. 5.1. Features 1-3 are due to impact craters, 4-6 are due to uneven topography. **5.3:** The themis map aligning with the region. The uneven topography responsible for clutter examples 4-6 are more apparent in this image.

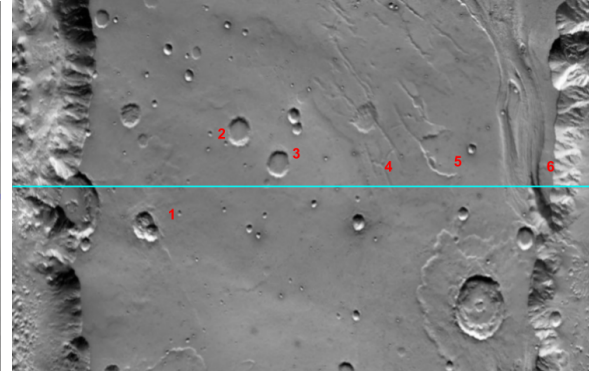


Fig. 5.3: THEMIS Map Location of SHARAD Track 4518601

5.3 Time Delay Measurement

After having mapped the true SHARAD reflections, we then measure the average time delay of each detection. We do this by opening up the radargram in Adobe Photoshop. We measure the pixel count between the bottom of the basal reflection to the bottom of the surface reflection. SHARAD data resolution is returned such that each pixel is equivalent to 37.5 ns (Seu *et al.* 2007). Therefore we multiply the pixel count by 37.5 to measure the time delay of each observation.

6 Step 3: Visible and Spectral Data Analysis

Step 3 of this project is to cross-reference the mapped basal reflections with visible and spectral data to identify a correlation with presence of LTDs and phyllosilicates. This cross referencing is to confirm the presence of the desiccated terrain at the sites of the SHARAD detection and expand detection of these deposits beyond where cameras that probe only the top millimeters can detect.

6.1 HiRISE and Polygonal Fractures

HiRISE and CTX images are analyzed for the presence of polygonally fractured units (Fig. 1.4) and LTDs within the regions that the basal reflections are observed. If the polygonal fractures are found to occur at or around the basal reflections, then that will lend support to all three of our current hypotheses discussed in Section 3.

6.1.1 Dimensional Analysis

Once the polygonal fractures have been identified, we conduct a dimensional analysis on them. We go through each locally fractured unit identified to measure an average width of the polygons. The polygon widths are measured at the thickest part of the polygon (Fig. 6.1). Further, we measure the lengths of the shadows (L) cast by the polygons in order to calculate the height from rim to trough of each unit, assuming a flat base (Fig. 6.1). This height is representative of the thickness of the polygons. We calculate the thickness (h) by the following equation:

$$h = L \tan(\theta_i) \quad (6.1)$$

Where θ_i is the incidence angle of the sun. θ_i is provided in data tables for each image. This will allow us to set a minimum thickness for the phyllosilicate deposits we hypothesize are associated with the polygonal fractures.

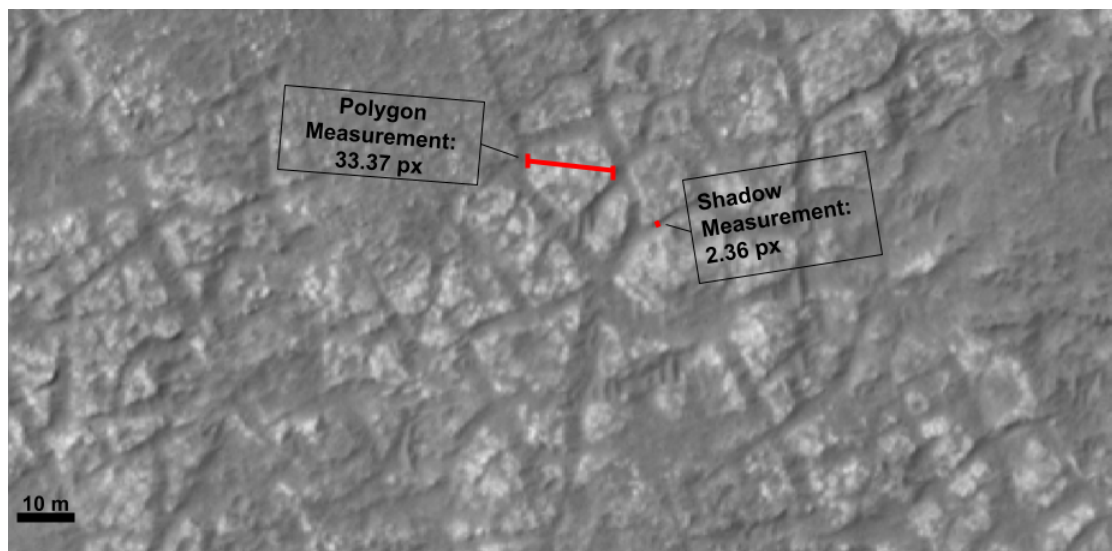


Fig. 6.1: Sample Polygon and Shadow Measurements

This figure highlights the technique used to determine the polygon width and polygon thickness of polygonal fractures. The polygon widths are measured from the widest point across in terms of pixels, that are later converted to meters. The same process is true for the shadow measurements. Shadow measurements are conducted in parallel to the incident angle of the sun. The resolution of this particular example image is 50 cm/px, making the polygon width and shadow length respectively 16.69 m wide and 1.18 m thick (NASA/JPL/University of Arizona).

6.2 CRISM Analysis

We use a prepared CRISM map (Fig. 1.2) of Al and Fe/Mg phyllosilicates and other hydrated minerals to identify the presence of Fe/Mg phyllosilicate deposits across Aurorae Planum. Additionally this analysis is to confirm the presence of the exhumed Fe/Mg phyllosilicates specifically within the locations of the SHARAD reflections and the polygonal fractures. This data is unpublished data provided by Christina Viviano, a collaborator of Isaac Smith on a related project.

7 Step 4: Data Comparison

The final step of this research will be to compare the lab-measured dielectric permittivity values to the calculated permittivity values of the Ganges phyllosilicates from the SHARAD data. Comparing the lab based measurements with the observed data will allow us to constrain a water weight percentage of those phyllosilicates necessary to allow SHARAD radar to transmit through and reflect back to the instrument.

7.1 Observed Depth Calculations

The time delays (t) of the reflectors in the SHARAD data can be used to calculate the reflector depth (d) in relation to the measured phyllosilicate ϵ' (Campbell *et al.* 2008):

$$d = \frac{tc}{2\sqrt{\epsilon'}} \quad (7.1)$$

Where c is the speed of light.

7.2 Critical Depth Calculations

We then use the measured ϵ' and $\tan\delta$ from Section 4 to calculate the maximum thickness (h) a layer of the phyllosilicate sample can be before the SHARAD signal is attenuated beyond the noise floor of -24 dB (Stillman & Grimm 2011). We use the Power Loss equation (Campbell *et al.* 2008):

$$L = \frac{P(h)}{P_0} = \exp\left(\frac{-8\pi h}{\lambda_0} \sqrt{\frac{\epsilon'}{2}(\sqrt{1 + \tan^2 \delta} - 1)}\right) \quad (7.2)$$

Where P_0 is the initial power at the surface of the first unit, $P(h)$ is the power returned to the surface based on traveling through the unit, h is the depth of the reflection, and λ_0 is

the center frequency of SHARAD. We can use this equation to solve for the critical depth of a unit, in which the power is attenuated to a weak, but minimally detectable signal. To do this, we set P_h to 6 dB above the noise floor estimated by Stillman & Grimm (2011), at -18 dB. 6 dB is considered a weak detection above noise, and therefore is a satisfactory minimum value for the purposes of this study. Rewriting Equation 7.2 in terms of h , we solve for the critical depth:

$$h = -\frac{\lambda_0 \ln(L)}{8\pi \sqrt{\frac{\epsilon'}{2}(\sqrt{1 + \tan^2 \delta} - 1)}} \quad (7.3)$$

This value of h is calculated using the lab based ϵ' and $\tan \delta$ results from Section 4. H can be compared to the layer thickness attained from our SHARAD measurements and shadow length measurements in order to confirm whether the clays have been dried sufficiently to allow full transmission and reflection back to the instrument.

8 Step 5: Saturation Experiment

In order to explore the validity of polygonal fracture formation and dehydration as a mechanism for lowering the $\tan\delta$ of the materials, we conduct an experiment with saturating the clays. The first experiment is to fully saturate a powdered phyllosilicate sample to be left to desiccate over the course of two weeks. The mass of the sample will be monitored to track water loss over time. This will help validate desiccation as a form of water loss. Additionally, we will compare the size of the polygons we form in the lab to those of what we observe on Mars at Aurorae Planum. This will support whether desiccation is a valid formation process for these particular formations at our study region. Further, we explore the effects of Mars pressures on desiccation, as Earth pressures are not sufficient to match what phyllosilicates on Mars experience.

8.1 Dehydration Methods

To conduct this experiment, we lay the clay powder out on a baking sheet (Fig. 8.1) and slowly stir water into it until it is of a sticky and wood putty-like consistency ensuring that all water has been adsorbed and there is no excess water. The resulting clay patty appears as Fig. 8.2. We measure the mass of the sheet before adding the clay, after adding the clay, and after saturation. Over the course of three days, we monitor the dehydration of the sample, measuring its mass each day. After those three days, we let the sample sit and further dehydrate for a week and a half, and again monitor the changes. The half a week addition to the experiment time is due to COVID restrictions disallowing access to the lab.

8.2 Polygonal Fracture Comparison

After the dehydration experiment is complete, we conduct a dimensional analysis on the newly formed polygons discussed in the previous section. This analysis will be used to gauge a correlation between the thicknesses and widths between our lab based desiccation

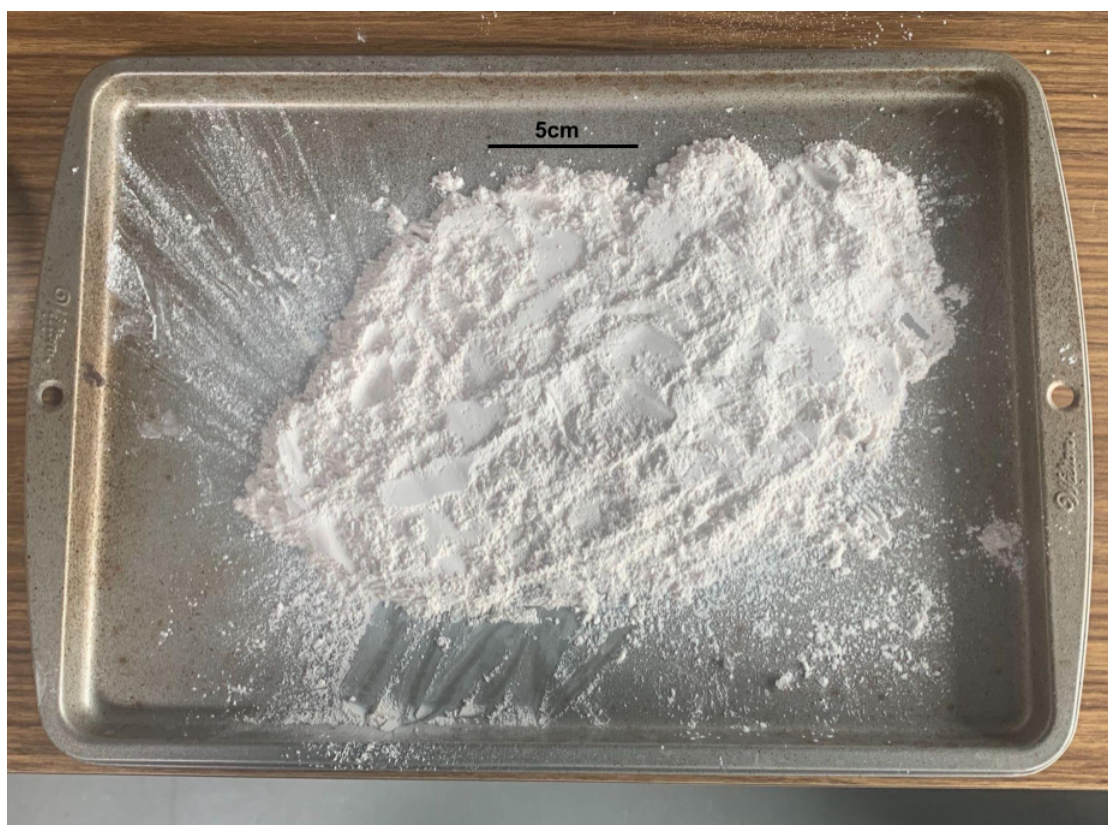


Fig. 8.1: Powdered Stx-1b Sample Before Hydration

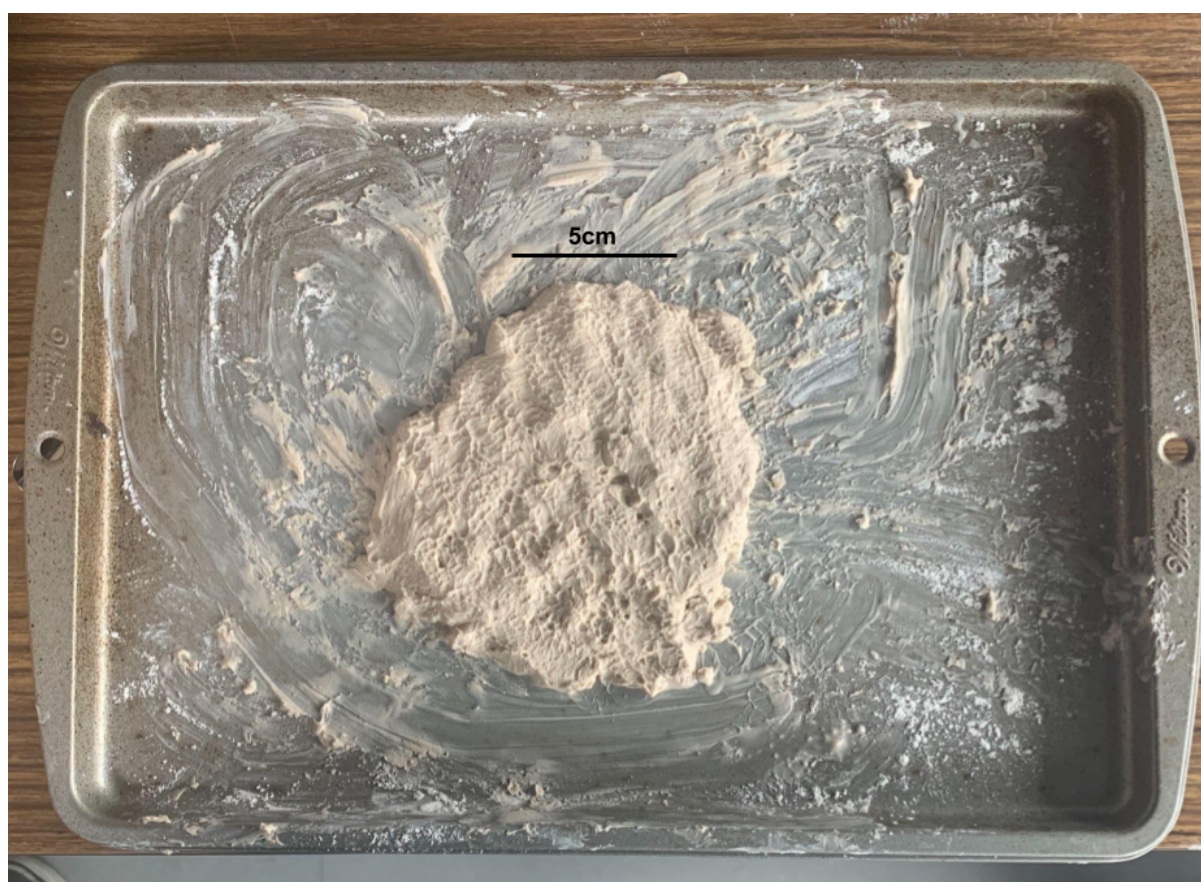


Fig. 8.2: Stx-1b Sample After Hydration

experiment and the desiccation fractures we observe on Mars. A positive correlation will provide support for our water table retreat hypothesis. This analysis is similar in form to the procedure discussed in Section 6.1.1. We measure the thicknesses and widths of the major fractures, as well as the minor fractures that form off to the sides from thinner remnant layers. We then compare the polygon widths and thicknesses observed at Aurorae Planum to those we have formed in the lab.

8.3 Vacuum Dehydration

Mars pressure is far lower than that of Earth (760 Torr), at ~ 5 Torr. The adsorbent properties of phyllosilicates leaves them susceptible to the fluctuating humidity of its ambient environment. Therefore in a near vacuum, such as on the surface of Mars, desiccation will be more extreme than on Earth, implying greater loss of mass post hydration. The experiments previously described in this section are insufficient at modeling this, and therefore we conduct this experiment to account for that discrepancy. We place a phyllosilicate sample in a vacuum chamber for 2 weeks beginning at ~ 5 Torr in order to monitor its dehydration in the vacuum. We measure the mass of the sample before placing it in vacuum, and then again after sitting in vacuum for two weeks to ascertain the water weight percentage it has lost in that time. We can compare these results to that of our experimental results from Section 4 to justify dehydration on the surface of Mars.

9 Results

9.1 Dielectric Laboratory Measurement Results

We have conducted three experiments using samples of Ca-Montmorillonite (stx-1b), a commercially available Fe/Mg phyllosilicate (Fig. 9.1). The first sample, we use as our control, was packed into the airline directly from the jar as a pristine sample. The other two samples are baked for 24 hours at 100 °C and 200 °C, respectively. We followed the methods in Sections 4.2 and 4.4. The masses and bulk density of each sample is presented in Table 9.1. Additionally, we calculate η of each sample.

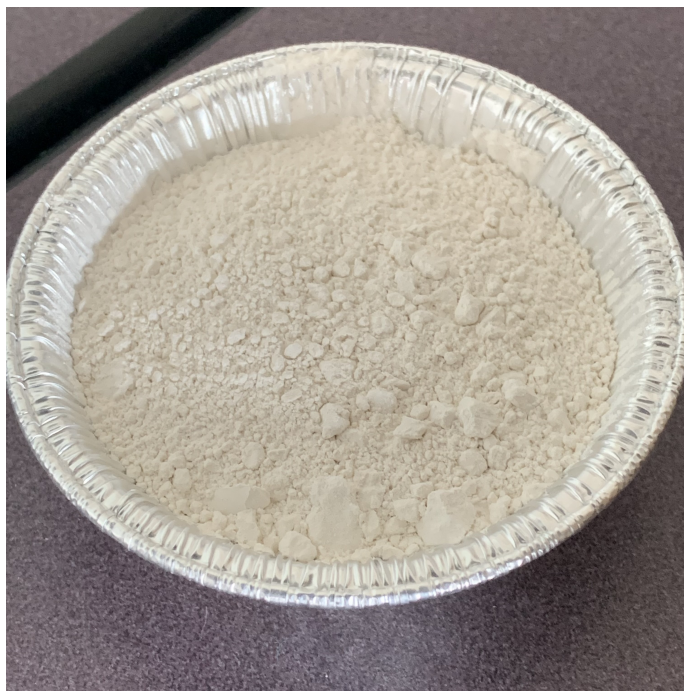


Fig. 9.1: Pristine stx-1b Ca-Montmorillonite

A sample of powdered stx-1b Ca-Montmorillonite phyllosilicate. The sample is referred to as "pristine" because it is directly from the sample jar, untouched since its packaging at the Clay Minerals Society.

	Sample Mass Before Bake (g)	Sample Mass After Bake (g)	Water Mass Lost from Control(%)	Bulk Density (g/cm^3)
Control	17.8372	NA	NA	0.9609
Stx-1b Baked at 100 °C	20.965	19.3224	7.84	0.85761
Stx-1b Baked at 200 °C	21.0981	17.8372	10.18	0.7893

TABLE 9.1: Water Loss Results

The resulting data from our baking experiments of stx-1b. The control sample is measured at ambient room humidity.

9.1.1 Control Sample

In the S-Parameter data of the Control measurement, we observe a clear dampening effect, muting the reflected and transmitted signals at higher frequencies (Fig. 9.2). This dampening effect is indicative of a sharply dropping permittivity and loss tangent, as we observe in the resulting dielectric plots that are calculated using permittivitycalc (Boivin & Hickson 2020) (Fig. 9.3, Fig. 9.4). The control measurement at SHARAD's center frequency of 20 MHz yielded a relatively high ϵ' and $\tan\delta$ at 19.66 ± 0.41 and 0.51 ± 0.02 , respectively (Table 9.2).

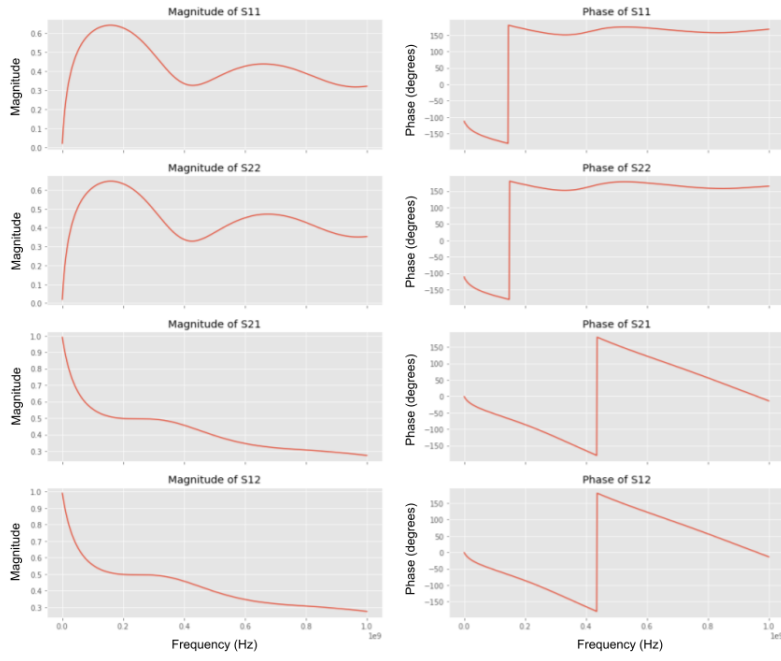


Fig. 9.2: S-Parameter Plot of Control stx-1b

Measured magnitudes of reflection and transmission S-parameters and their respective phases for the control measurement of stx-1b. This data is presented in the same way as described for Figure 4.10.

9.1.2 100 °C Sample

In the S-Parameter data, it is observed that the dampening from the previous sample is not apparent (Fig. 9.5). That signifies that the properties are far more stable. We observe a dissimilarity between S_{11} and S_{22} in both the Magnitude and Phase at the major resonance point. The major resonances occur at harmonic node points inherent to the 15 cm length of the airline. This is likely due to a slight air gap in the sample. It does appear in a sudden drop in the permittivity plots, however, it does not affect the frequency range that

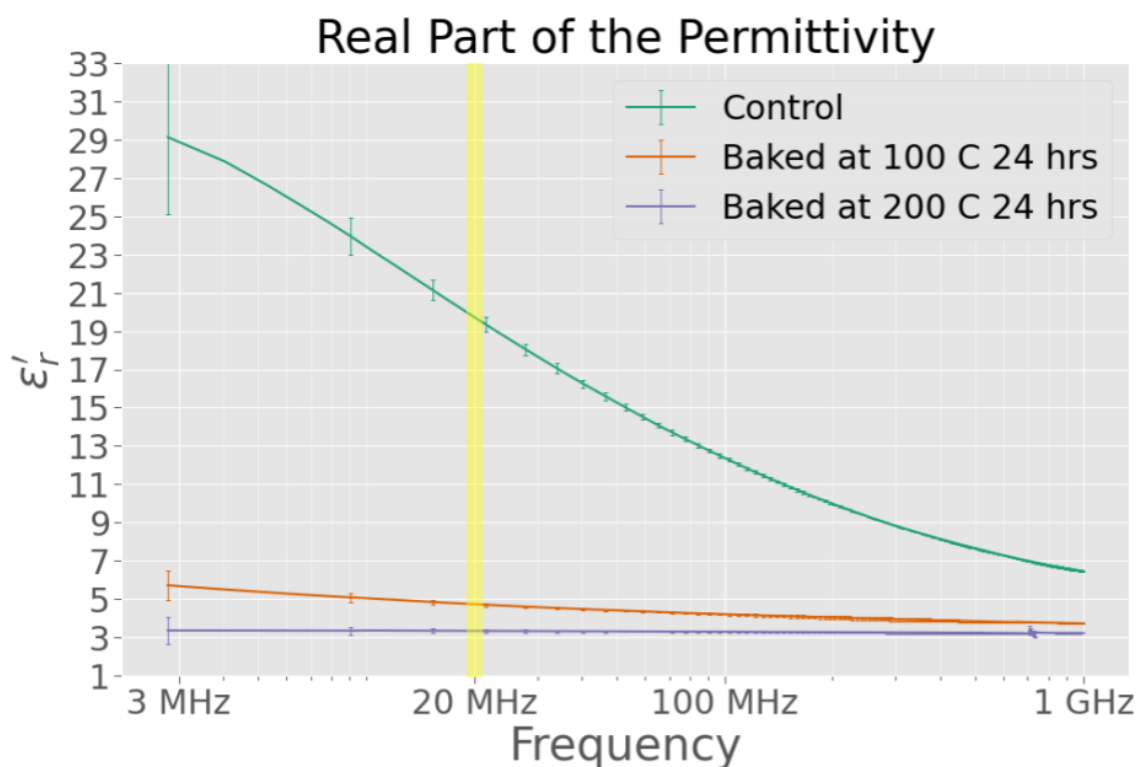


Fig. 9.3: Lab Measured ϵ' for Stx-1b at Various Hydration States

Comparison of the ϵ' calculated using permittivitycalc for the control sample, the sample baked at 100 °C for 24 hours, and the sample baked at 200 °C for 24 hours. The yellow bar marks the center operational frequency of the SHARAD instrument.

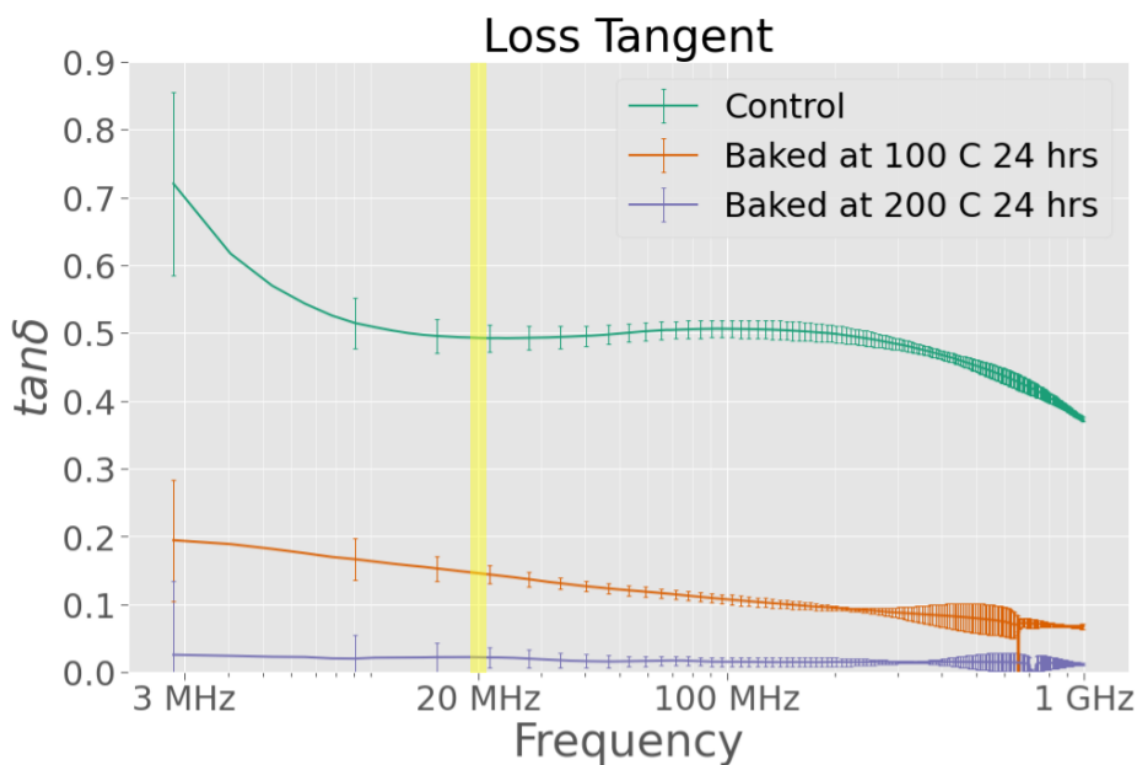


Fig. 9.4: Lab Measured $\tan\delta$ for Stx-1b at Various Hydration States

Comparison of the $\tan\delta$ calculated using permittivitycalc for the control sample, the sample baked at 100 °C for 24 hours, and the sample baked at 200 °C for 24 hours. The yellow bar marks the center operational frequency of the SHARAD instrument.

we are concerned with at 20MHz (Fig. 9.3, Fig. 9.4).

When compared to control measurement, the dielectric values change drastically after baking at 100 °C for 24 hours. ϵ' dropped to 4.74 ± 0.10 and $\tan\delta$ drops to 0.146 ± 0.014 . This drop in loss and permittivity is significant, as the sample only experienced a water mass loss of 7.84% from the control sample (Table 9.2).

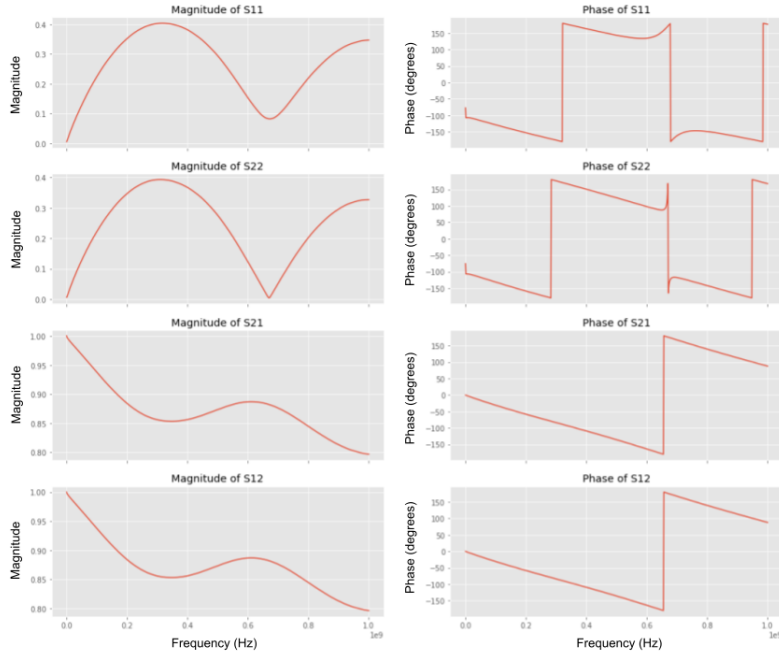


Fig. 9.5: S-Parameter Plot of stx-1b after Baking at 100 °C

Measured magnitudes of reflection and transmission S-parameters and their respective phases for a sample of stx-1b that has been baked at 100 °C for 24 hours.

9.1.3 200 °C Sample

In the S-Parameter data of the sample baked at 200 °C, we observe significant increase in transmission and a decrease in reflection from the previously discussed sample (Fig. 9.6). As with the previous sample, there is a discrepancy noticed at resonance which does not affect the data at 20 MHz (Fig. 9.3, Fig. 9.4). The trend of the permittivity and loss appears to have stabilized with very little change in value over the measured frequency range. Further, the sample baked at 200 °C exhibited a further decrease in permittivity and loss compared to the previous two measurements. We measure values of 3.35 ± 0.1 for permittivity and 0.022 ± 0.017 for loss. The loss tangent experiences yet another drastic drop, despite the sample only losing $\sim 2\%$ more water weight than the 100 °C sample (Table 9.2).

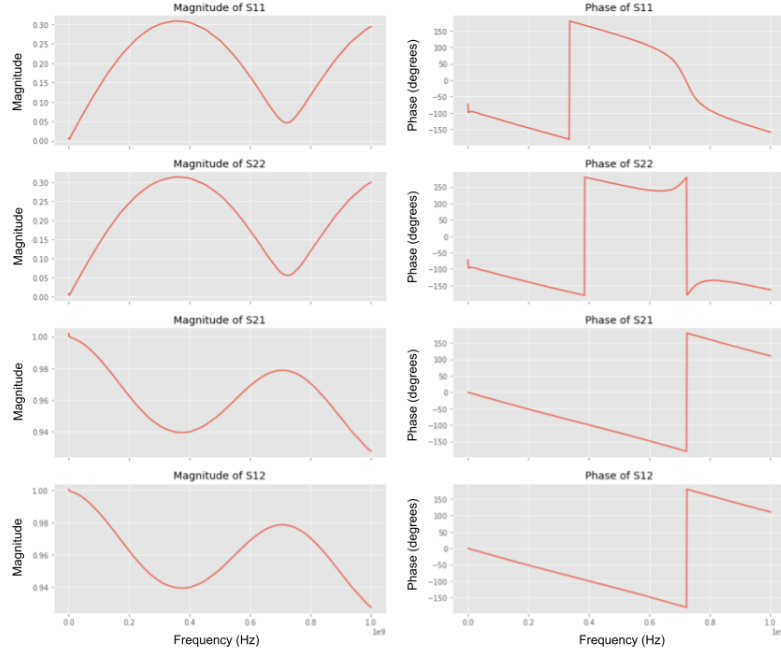


Fig. 9.6: S-Parameter Plot of stx-1b after Baking at 200 °C

Measured magnitudes of reflection and transmission S-parameters and their respective phases for a sample of stx-1b that has been baked at 200 °C for 24 hours.

	ϵ' @ 20MHz	ϵ'' @ 20MHz	$\tan\delta$ @ 20MHz
Control	19.66 ± 0.41	6.38 ± 0.36	0.49 ± 0.02
Stx-1b Baked at 100 °C	4.74 ± 0.1	0.43 ± 0.07	0.15 ± 0.01
Stx-1b Baked at 200 °C	3.35 ± 0.1	0.04 ± 0.05	0.02 ± 0.02

TABLE 9.2: Dielectric Properties of Stx-1b at SHARAD Operating Frequency

Presented results of the dielectric measurements conducted on samples of stx-1b at varied states of hydration.

9.2 SHARAD Analysis Results

9.2.1 Basal Reflection Map

We analyzed 208 radar tracks over Aurorae Planum. Of the 208 we analyzed, 44 contained basal reflections over the plateau (Table 9.3). These basal reflections are skewed towards the western side of Aurorae Planum (Fig. 9.7). The eastern portion of the plateau reveals fewer concentrations of basal reflections. We separate the three main collections of reflections in the west as Regions A, B, and C (Fig. 9.7). Region A, being in the basin just south of Elaver Valles and Morella Crater. Region B, within Morella crater, and Region C on the plateau to the northeast of Morella Crater. There is a bit of discrepancy in some regions where we do not observe basal reflections that are key regions of the outflow event that pooling is predicted to have occurred (Section 3). Those sections are the western half

of Morella crater and around its rims, and around the basin retreat channel, in the northern tip of the southern flood basin (Fig. 1.6, Fig. 9.7). These discrepancies are noted due to poor geometric conditions that cause copious levels of clutter, making it difficult to discern and justify true reflections. In the case of Morella Crater, we attribute this to the rim of the crater and the rim of Ganges Cavus. On the western side of the southern basin, there is a large crater with a significant ejecta blanket that causes a significant amount of clutter due to the uneven terrain. Several other gaps in key regions are due to poorly returned data providing fuzzy and impossible to discern radargrams.

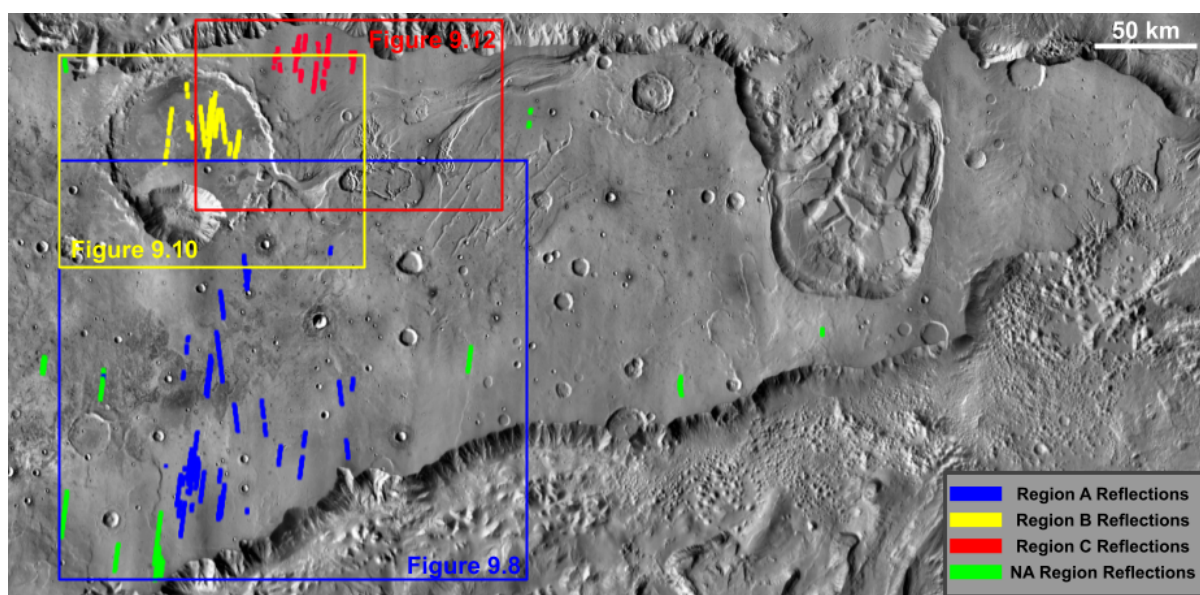


Fig. 9.7: Divided Study Region Map

A map of the basal reflections identified with SHARAD data, divided into four separate regions: Region A, in the southern basin; Region B, within Morella Crater; Region C, on the northern flatlands; and non-applicable regions, where the basal reflections are not geographically tied to a particular region. Basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

9.2.2 Time Delay Analysis Results

We conducted a depth analysis on the radar detections of the three regions using the procedure detailed in Section 5.3 . Region A yielded reflections an average of 313 ns below the surface (Figs. 9.8 and 9.9), region B, 270 ns (Figs. 9.10 and 9.11), and region C, 313 ns (Figs. 9.12 and 9.13). All reflections that were measured were found to be either under or greater than the 250 ns time delay considered for a side lobe. While some detections are found around that range, they are not parallel to the surface and therefore we argue are not processing artifacts. One such example of this is the detections highlighted in Figure 9.8. A full list of time delays can be seen in Table 9.3.

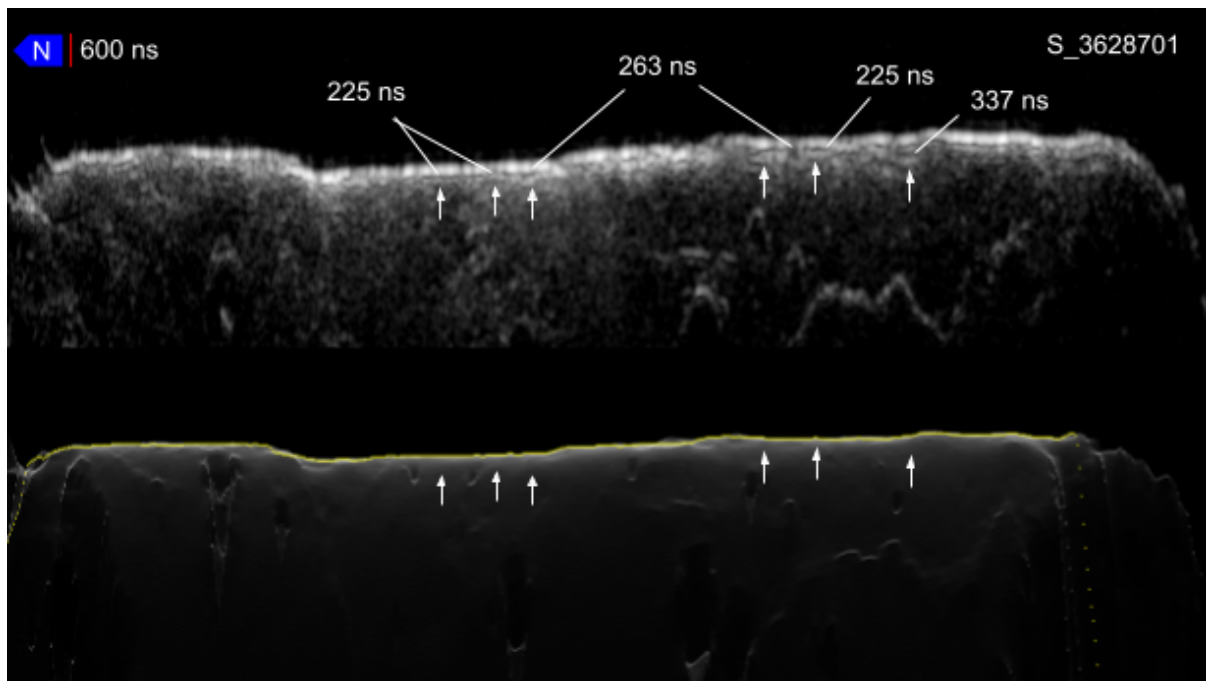


Fig. 9.8: Region A Reflections and Simulated Clutter Model

Data from SHARAD track 3628701 with comparison to its respective clutter model. The blue N arrow refers to the direction of North, while the red bar is representative of the time scale. The white arrows point to the true reflections in the data, and the lack thereof in the simulated clutter model.

SHARAD Track ID	Detection Region	Average Time Delay (ns)
4551801	B	200.00 $\pm$ 21.65
4815501	N/A	206.25 $\pm$ 20.54
3805401	C	215.63 $\pm$ 26.52
3628701	A	216.35 $\pm$ 37.98
3742101	B	216.67 $\pm$ 16.54
3544301	C	225.00 $\pm$ 23.72
3684701	A-1	225.00 $\pm$ 34.72
4922301	N/A	225.00 $\pm$ 32.48
4735701	B	228.75 $\pm$ 27.67
3649101	A-1	232.50 $\pm$ 34.46
4736401	B	235.71 $\pm$ 27.24
2792901	C	236.25 $\pm$ 30.87
3833101	B	237.50 $\pm$ 19.36
4836601	A	240.00 $\pm$ 20.54
2623901	N/A	246.43 $\pm$ 20.04
3246301	C	262.50 $\pm$ 56.17
4644101	B	262.50 $\pm$ 64.95
4078401	A	266.07 $\pm$ 65.92
3649801	A	272.92 $\pm$ 49.49
3825801	C	279.55 $\pm$ 38.84
2813801	C	282.69 $\pm$ 91.36
3508701	A	282.95 $\pm$ 25.78
3544301	A	285.00 $\pm$ 20.54
3721001	A	293.75 $\pm$ 28.23
2645001	A	300.00 $\pm$ 20.04
3585801	B	302.88 $\pm$ 47.09
3649801	A	305.92 $\pm$ 61.57
3685401	B	312.50 $\pm$ 83.85
4835901	C	315.00 $\pm$ 30.62
4056602	C	318.75 $\pm$ 37.50
3784301	A	337.50 $\pm$ 23.72
3832401	B	337.50 $\pm$ 0.00
3607601	A	340.91 $\pm$ 65.93
3628701	A	345.00 $\pm$ 70.52
3784301	B	356.25 $\pm$ 21.65
3508701	B	360.00 $\pm$ 56.87
4950001	A	360.00 $\pm$ 20.54
2687201	A	369.23 $\pm$ 71.56
3543601	N/A	388.64 $\pm$ 34.67
2666101	A	420.00 $\pm$ 84.41
3826501	A	423.75 $\pm$ 44.90
2645001	C	427.50 $\pm$ 20.54
4737701	N/A	431.25 $\pm$ 21.65
3649101	A-2	437.50 $\pm$ 73.74
3684701	A-2	440.63 $\pm$ 123.90
4114010	C	450.00 $\pm$ 0.00
3543601	C	453.41 $\pm$ 45.79
4836601	C	460.23 $\pm$ 80.59
3593701	N/A	512.50 $\pm$ 21.65
3686701	N/A	512.50 $\pm$ 43.30
3459901	N/A	555.00 $\pm$ 76.85
3458601	N/A	652.50 $\pm$ 20.54
4683010	N/A	652.50 $\pm$ 20.54

TABLE 9.3: Basal Reflection Positive SHARAD Tracks and their Average Time Delays

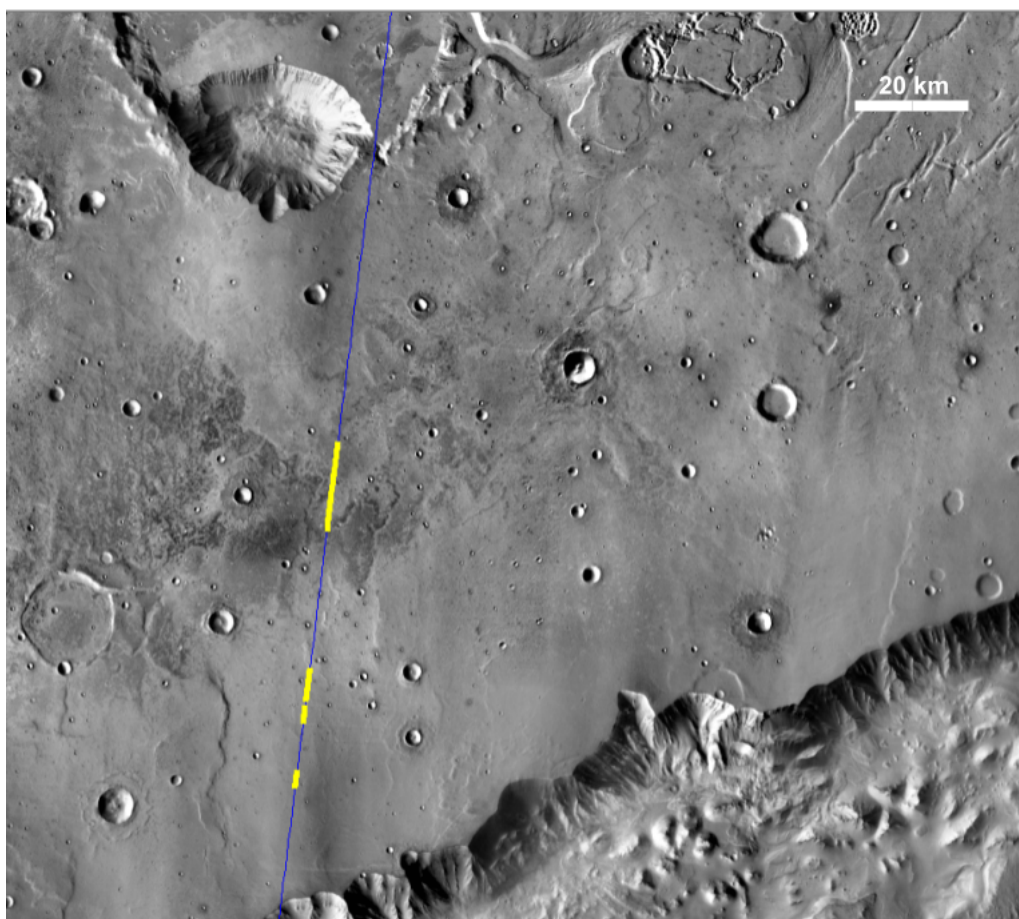


Fig. 9.9: Contextual Map for Fig. 9.8

The SHARAD track is represented by the blue line. The detections are represented by the yellow. The basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

9.3 HiRISE and CRISM Analysis Results

9.3.1 Polygonal Fracture Observations

HiRISE observations, while limited to only a few, have revealed that within region A and B, there exists the presence of widespread polygonally fractured terrain. For region A, the polygonal fractures are observed in a string of HiRISE images moving along the path of the basin mentioned in Section 3.4 (Fig. 9.14). In some images, such as ESP_063471_1690, the northernmost image of region A (Fig. 9.14), the fractures appear mostly open and uncovered by sediment and aeolian deposition (between 308.72° E, -10.94° N and 308.80° E, -10.97° N) (Fig. 9.15). Others, such as within the southernmost image ESP_037203_1680, the fractures are mostly covered by sediment and aeolian deposits (between 308.82° E, -11.41° N and 308.83° E, -11.40° N) (Fig. 9.16). It appears

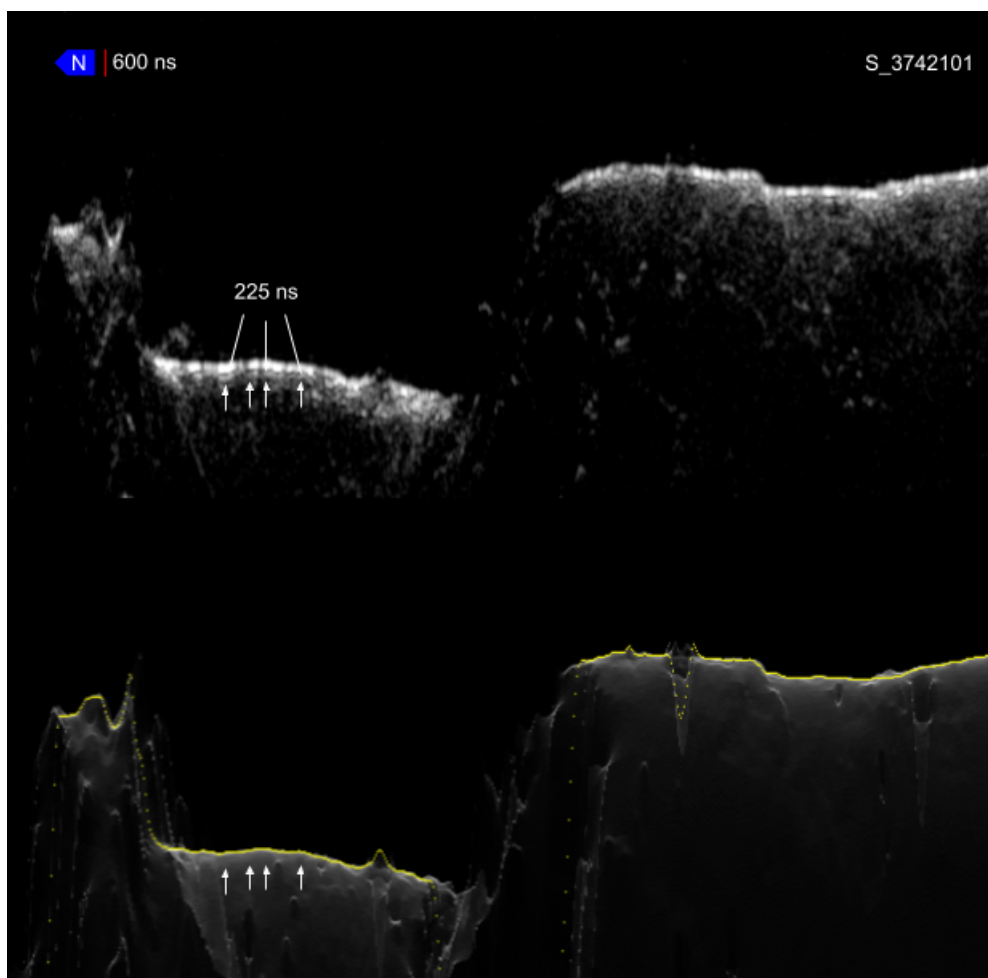


Fig. 9.10: Region B Reflections and Simulated Clutter Model

Data from SHARAD track 3742101 with comparison to its respective clutter model. The blue N arrow refers to the direction of North, while the red bar is representative of the time scale. The white arrows point to the true reflections in the data, and the lack thereof in the simulated clutter model.

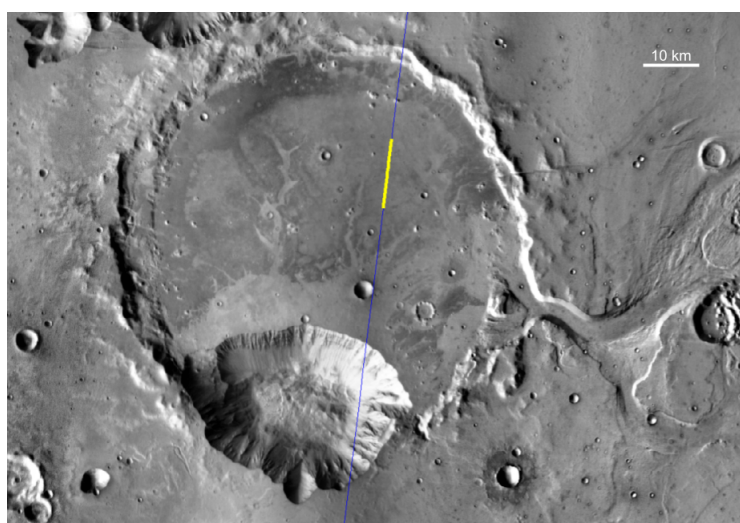


Fig. 9.11: Contextual Map for Fig. 9.10

The SHARAD track is represented by the blue line. The detections are represented by the yellow. The basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

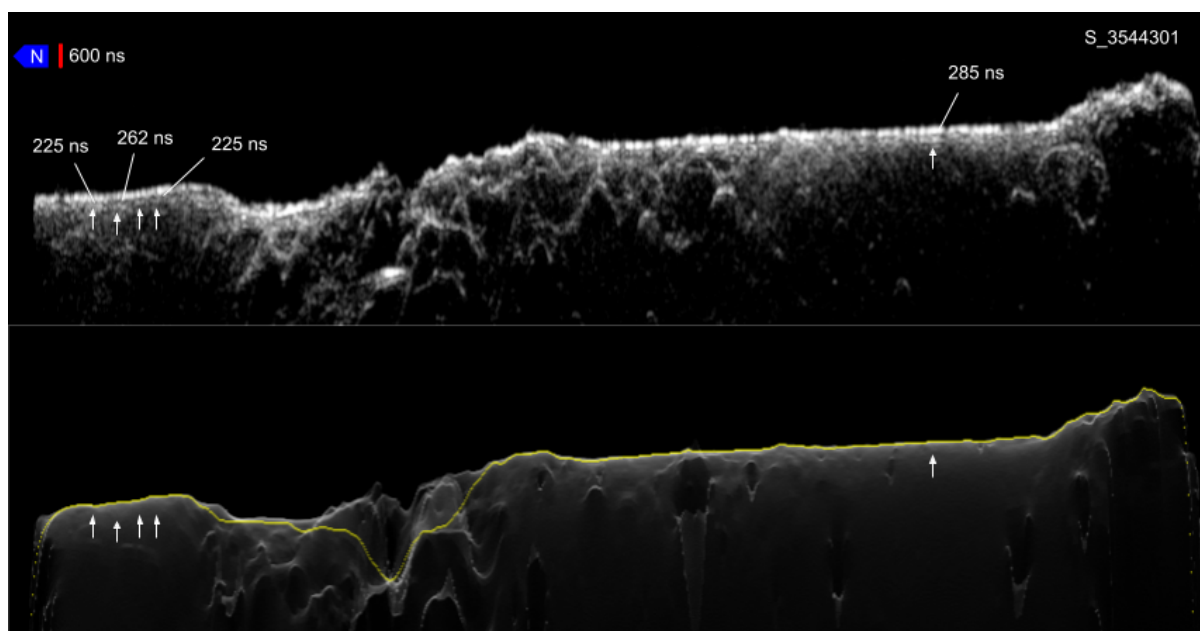


Fig. 9.12: Region C Reflections and Simulated Clutter Model

Data from SHARAD track 3544301 with comparison to its respective clutter model. The blue N arrow refers to the direction of North, while the red bar is representative of the time scale. The white arrows point to the true reflections in the data, and the lack thereof in the simulated clutter model. Also included on the far right is a detection from region A, in the same track.

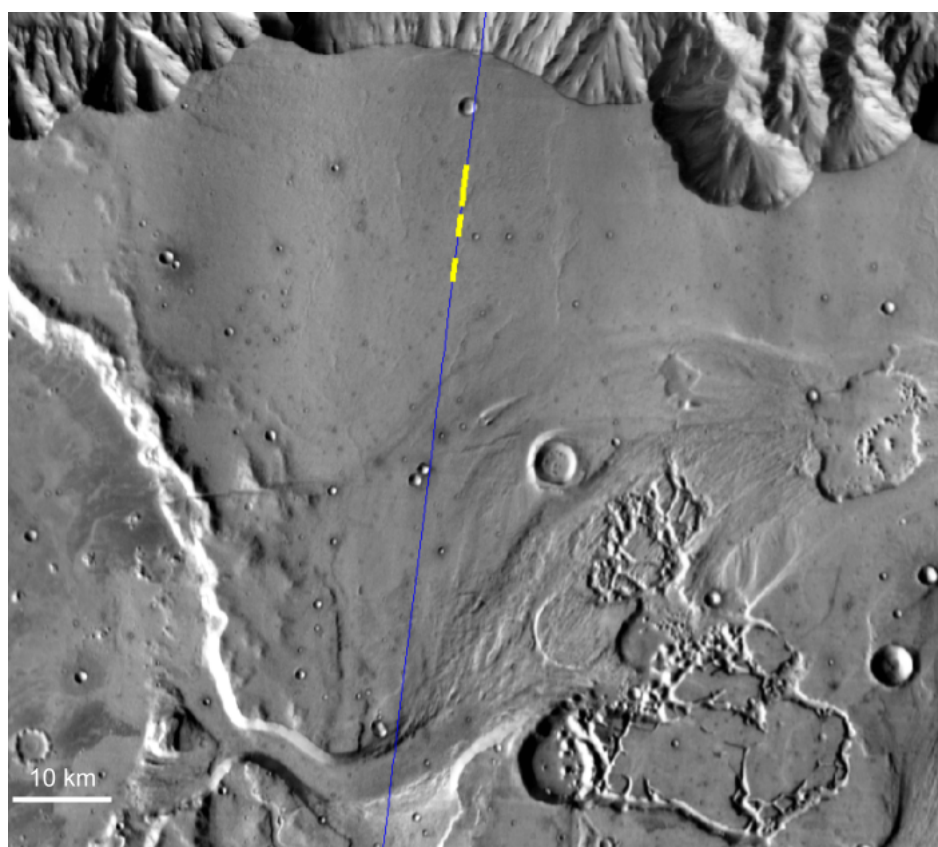


Fig. 9.13: Contextual Map for Fig. 9.12

The SHARAD track is represented by the blue line. The detections are represented by the yellow. The basemap uses THEMIS Day IR Global Mosaic data (THEMIS Team, Arizona State University).

that the location of these clear polygonal fractures aligns well with our SHARAD observation map (Fig. 9.14). Region B reveals very much the same story as Region A, in that the most clear and uncovered polygonal fractures (Fig. 9.18) appear near where our SHARAD observations are detected (Fig. 9.17). We were not able to confirm the presence of polygonal fractures at region C, although this may be due to resolution restrictions as there are no readily available HiRISE images over this region. We had to rely on Context Camera images (CTX) which have a significantly lower 6 m/px resolution that cannot resolve the tens of meters scale fractures, like HiRISE's 0.5 m/px resolution can. (Malin *et al.* 2007). However, we do observe evidence of LTDs in region C, which similarly resemble the polygons observed at region A in CTX imaging (Fig. 9.19), so we consider that significant of a correlation. The polygonally fractured units appear to be correlated with the locations that we identify the basal reflections from SHARAD.

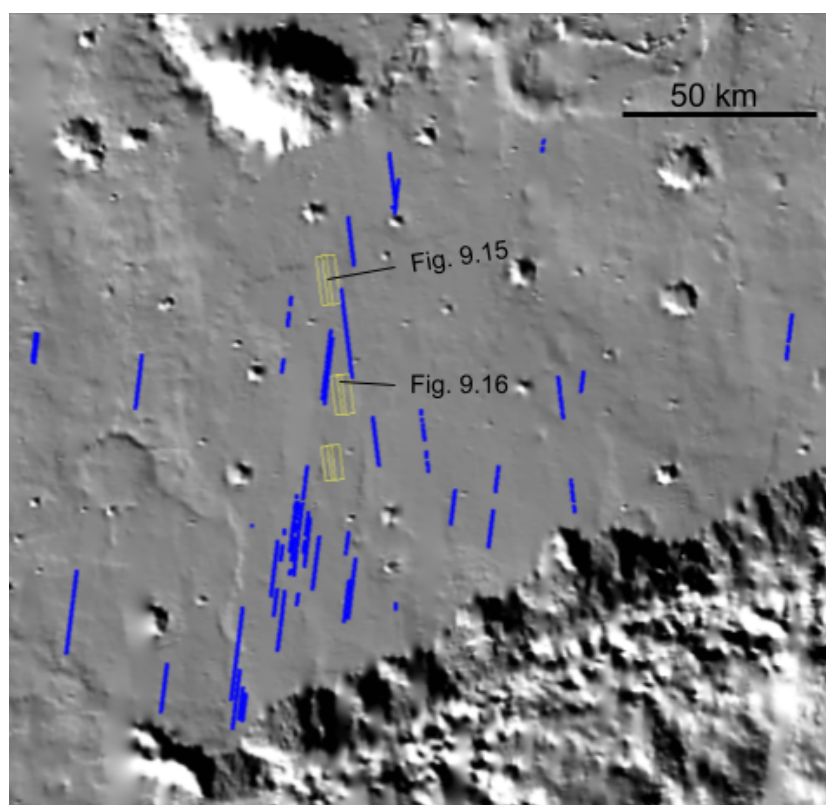


Fig. 9.14: HiRISE Image Locations Containing Clear Polygonal Fracturing in Region A
Basal reflection locations (blue) with reference to the HiRISE images that were identified to contain polygonal fractures (yellow outlines). Basemap uses MOLA Shaded Relief (NE) data (MOLA team Washington University, St.Louis).

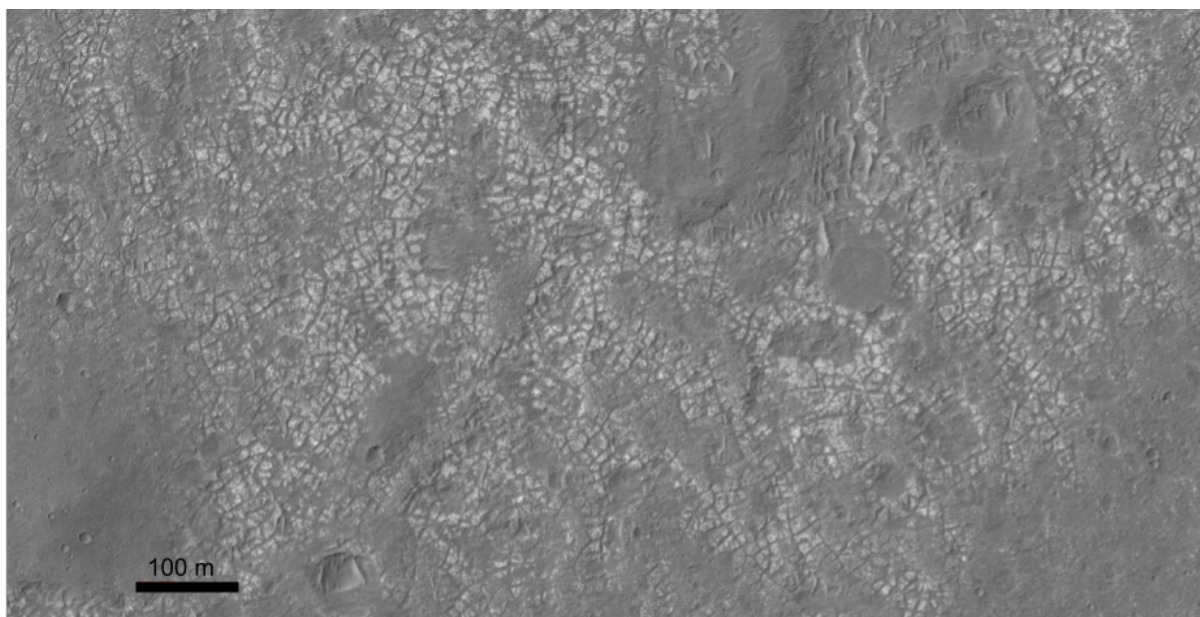


Fig. 9.15: Exhumed Polygonal Fractures Within HiRISE Image ESP_063471_1690 (NASA/JPL/University of Arizona)

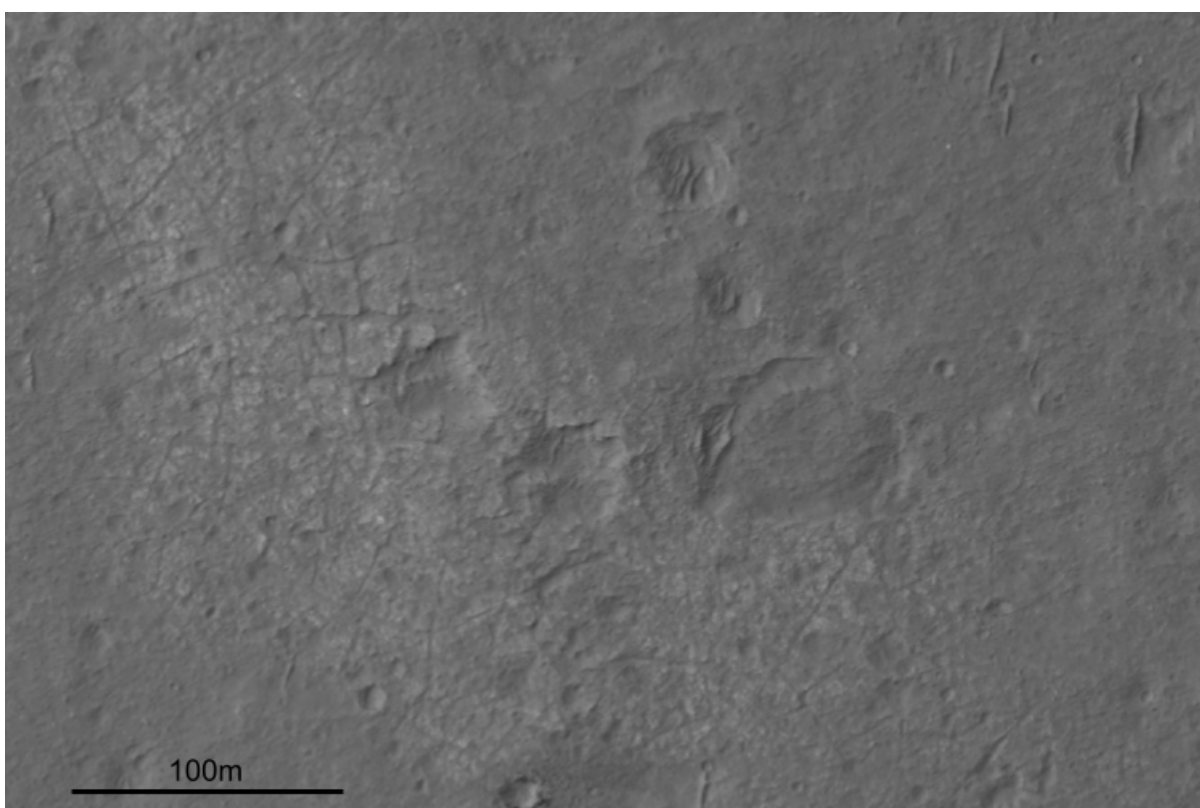


Fig. 9.16: Polygonal Fractures Covered by Dust Layering Within HiRISE Image ESP_037203_1680 (NASA/JPL/University of Arizona)

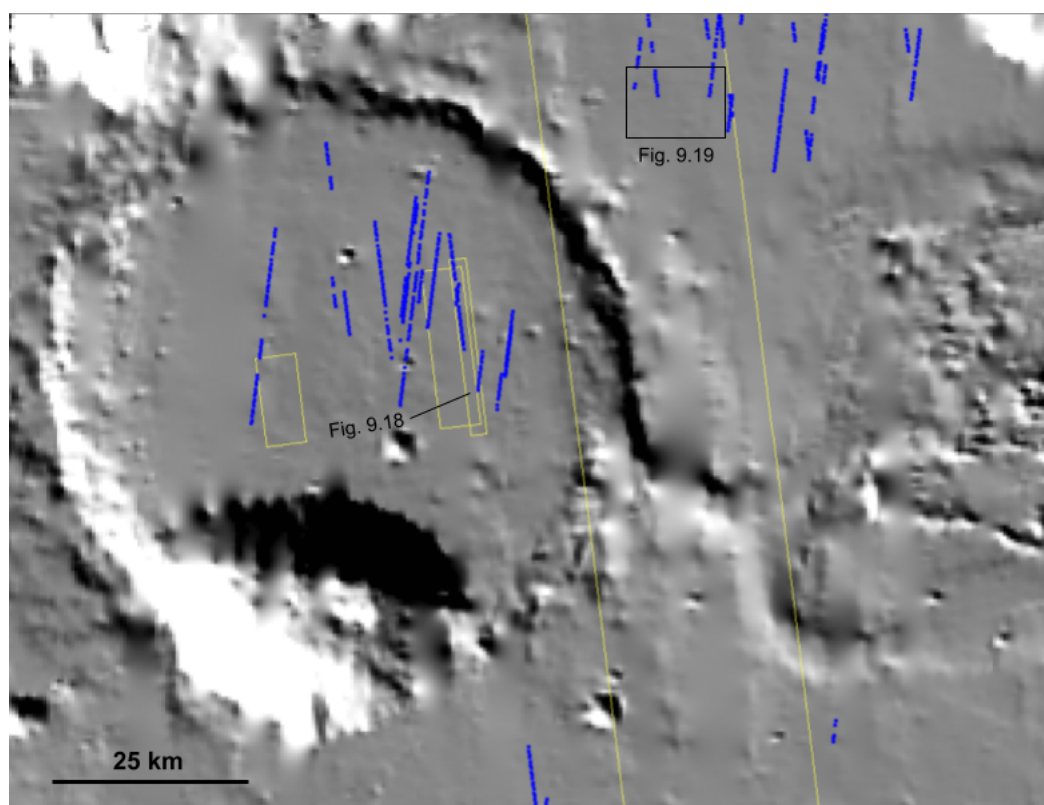


Fig. 9.17: Image Locations Containing Clear Polygonal Fracturing in Region B and C
Basal reflection locations (blue) with reference to the HiRISE images that were identified to contain polygonal fractures (yellow outlines). Basemap uses MOLA Shaded Relief (NE) data (MOLA team Washington University, St.Louis).

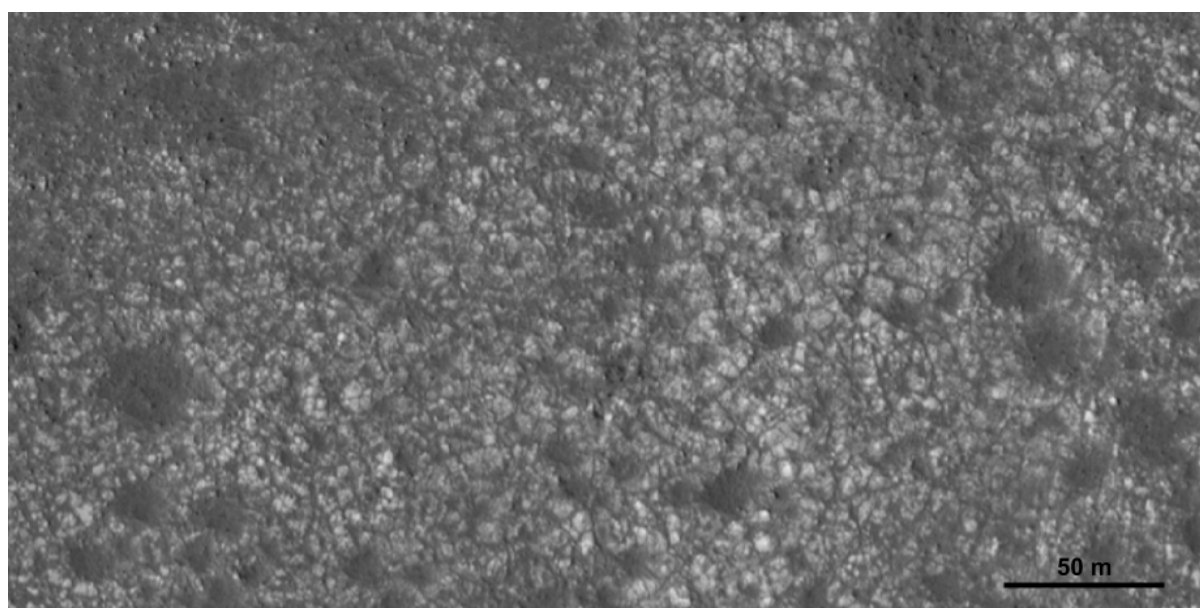


Fig. 9.18: Polygonal Fractures Within HiRISE Image PSP_003183_1705
(NASA/JPL/University of Arizona)

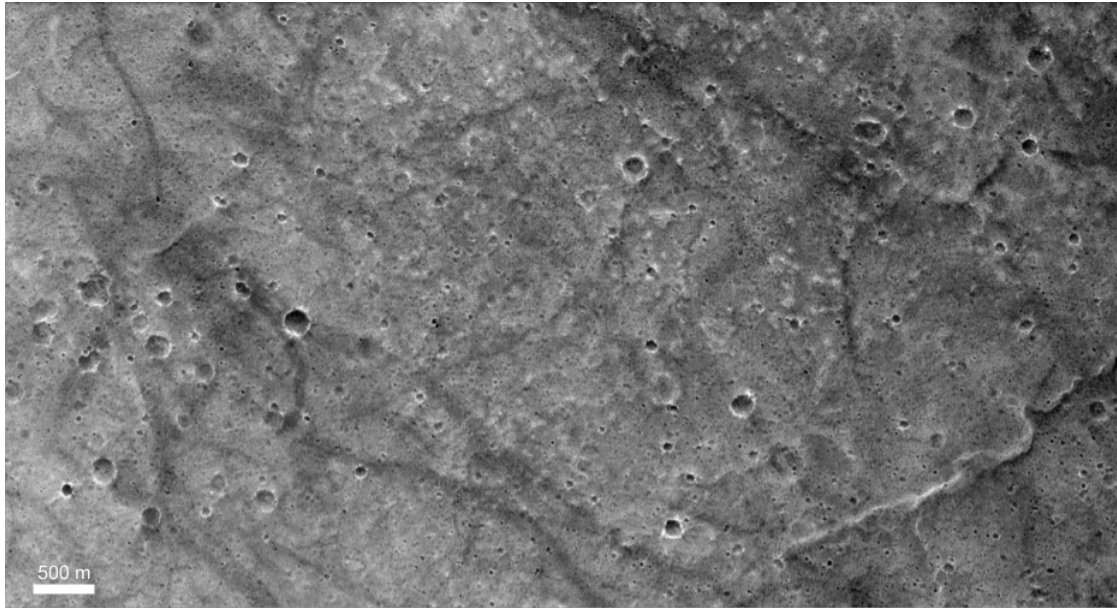


Fig. 9.19: Light Toned Deposits Within CTX Image P13_006229_1704_XN_09S050W (NASA/JPL/Arizona State University)

9.3.1.1 Polygonal Fracture Dimension

We measure the thickness of the the polygonal fractured units using the lengths of the shadows cast between their polygons following the methods highlighted in Section 6.1.1 (Fig. 6.1). We conduct this measurement several times for each designated region and use Equation 6.1 to calculate the polygon thickness. We take the average of each region, presented in Table 9.4. On average, we find that the shadow length measurements indicate a height difference between the top of the polygon and the trough to be between 1.5-3 m thick on average, implying the thickness for the surface phyllosilicate layers. We assume that the trough represents the bottom of the polygon, thereby giving us a minimum thickness for the deposits.

According to Equation 7.1, a phyllosilicate layer of 1.5-3 m, would need to have a ϵ' of 245 to match the 313 ns delays that we observe, which would require an unphysical number. We therefore interpret the results to mean that the base of the clay layer is not the interface that causes the SHARAD reflections. We assume this secondary interface to be a basaltic layer consistent with the interpretation.

We also measure the width of each polygon in order to gauge an average size of polygon

for each region. The polygons all measure in the scale of 10's of meters at their widest parts. The thinnest measuring ~ 8.5 m and the widest measuring ~ 27.5 m across. The full average results for each region can be seen in Table 9.4. We also divide the thickness by the width to gauge a scaling factor for the polygons. We plot this scaling factor against the log of the widths of the polygons in order to gauge how well thickness scales to the size of the polygons (Fig. 9.20).

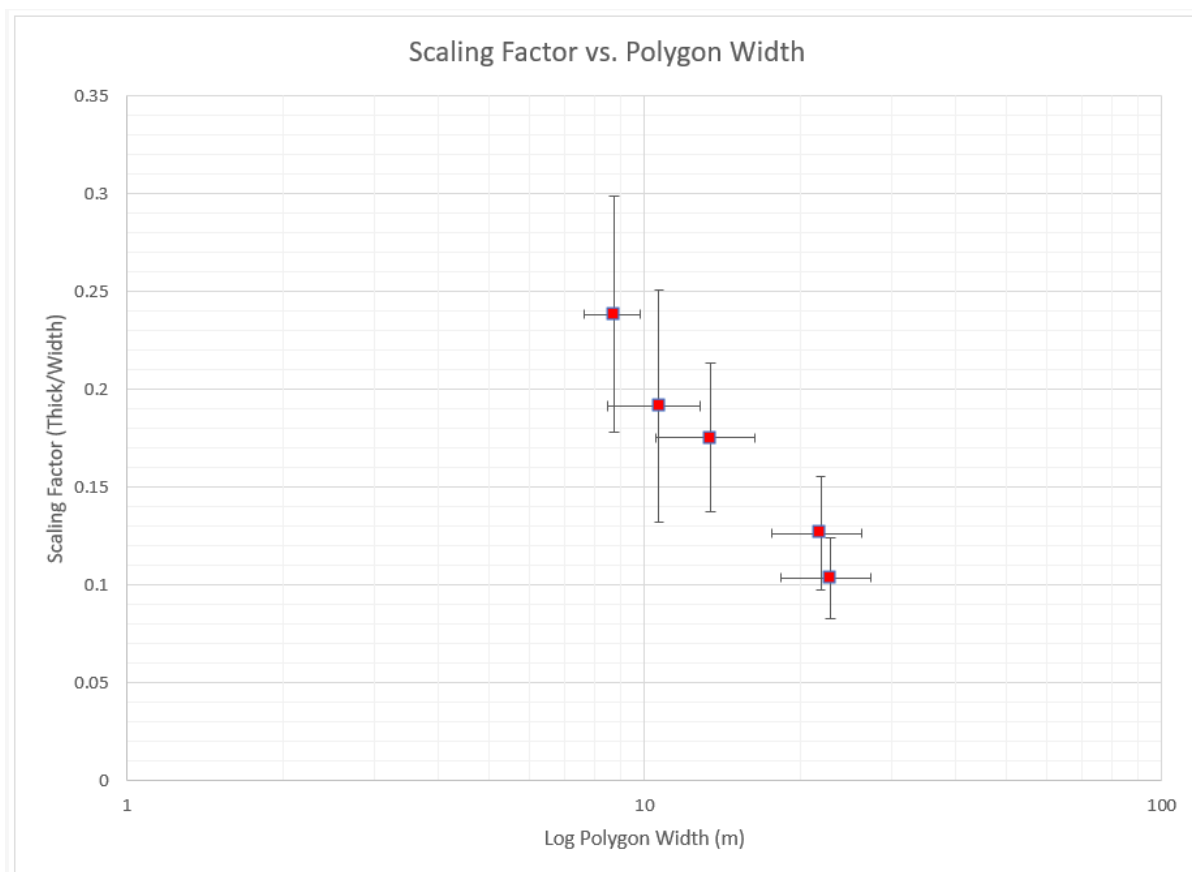


Fig. 9.20: Plot of Polygon Scaling Factor to Polygon Width of Mars' Polygonal Fractures

HiRISE Image ID	Region	Average Polygon Width (m)	Average Polygon Thickness (m)	Scale Factor
ESP_012848_1705	B	8.73 ± 1.07	2.08 ± 0.46	0.24 ± 0.06
PSP_003183_1705	B	10.66 ± 2.05	2.04 ± 0.48	0.19 ± 0.06
ESP_063471_1690	A	13.43 ± 2.91	2.35 ± 0	0.18 ± 0.04
ESP_062113_1690	A	21.94 ± 4.31	2.78 ± 0.34	0.13 ± 0.03
ESP_037203_1680	A	22.87 ± 4.47	2.37 ± 0.09	0.10 ± 0.02

TABLE 9.4: Polygonal Fracture Dimensions Observed from HiRISE Imagery

9.3.2 CRISM Analysis Results

CRISM observations identify Fe/Mg Phyllosilicates richly throughout the region of Ganges Mensa (Fig. 1.2). The surface deposits are noted mostly along the edges of the chasmata.

However, other deposits are within the ejecta blankets of numerous craters around the region as a result of turnover, indicating these deposits are widespread, and covered in layers of younger material that blocks spectroscopic detections.

9.4 Data Comparison Results

9.4.1 Multi-Layer Depth Analysis

Based on the identification of the 1.5-3 m phyllosilicate layers of the polygonal fractures, we would expect the basal reflections to appear much sooner than we have identified in each region. We reason there must be a second layer that SHARAD travels through creating the reflections that we see. Thus, to understand what we're observing, we must use a multi-layer approach to estimate the depths of our observed basal reflections. We can assume two main layers for these radar tracks that will have the greatest affect on the attenuation. The first surface layer would be the proposed Fe/Mg phyllosilicate unit that is ~ 3 m thick. We then assume the remaining layer to be the Noachian era basaltic lava flow layers identified by Beyer & McEwen 2005, with $\epsilon' = 10$ (Carter *et al.* 2009). We then expand Equation 7.1 to incorporate this multi-layer system:

$$d = \frac{ct_1}{2\sqrt{\epsilon'_1}} + \frac{ct_2}{2\sqrt{\epsilon'_2}} \dots \quad (9.1)$$

We consider this calculation for the average time delays per region as presented in Section 9.2.2 for a range of phyllosilicate ϵ'_1 from 2-9. We calculate the first half of the equation, representing the first layer, using our observational results from Section 9.3.1.1. Although we have not been able to measure a thickness of Region C's assumed polygons, we use an estimated value of 2.35 m, the average of the thicknesses that we had measured for Region A and Region B's polygons. Assuming ϵ'_2 of the second layer is 10, we use Equation 9.1 to find that Region A's basal reflections fall between ~ 16 and ~ 15 m on average, region B's are between ~ 14 and ~ 13 m deep, and Region C's depths are between ~ 16 and ~ 15 m. The full results can be seen in Table 9.5.

	Region A	Region B	Region C
Depth with $\epsilon'_1 = 2$	16.24 $\pm$ 4.65	13.92 $\pm$ 3.71	16.12 $\pm$ 5.51
Depth with $\epsilon'_1 = 3$	15.99 $\pm$ 4.65	13.71 $\pm$ 3.72	15.89 $\pm$ 5.51
Depth with $\epsilon'_1 = 4$	15.78 $\pm$ 4.65	13.54 $\pm$ 3.72	15.69 $\pm$ 5.52
Depth with $\epsilon'_1 = 5$	15.59 $\pm$ 4.65	13.25 $\pm$ 3.72	15.52 $\pm$ 5.52
Depth with $\epsilon'_1 = 6$	15.42 $\pm$ 4.65	13.25 $\pm$ 3.72	15.36 $\pm$ 5.52
Depth with $\epsilon'_1 = 7$	15.27 $\pm$ 4.65	13.12 $\pm$ 3.72	15.22 $\pm$ 5.52
Depth with $\epsilon'_1 = 8$	15.12 $\pm$ 4.65	13.00 $\pm$ 3.72	15.08 $\pm$ 5.52
Depth with $\epsilon'_1 = 9$	14.996 $\pm$ 4.65	12.89 $\pm$ 3.72	14.96 $\pm$ 5.52

TABLE 9.5: Calculated Average Reflection Depths for Regions A, B, and C for Upper Layer ϵ' Values of 2-9

9.4.2 Critical Depth Calculations

We use the results presented in Section 9.1 with Equation 7.3 in order to Calculate the critical thickness of each sample that we measured. The control measurement yields a critical thickness of ~ 2.5 m. This is close to the thickness of the polygonal fractures we observe at Aurorae Planum, however that is coincidental, for the reasons mention in Section 9.3.1.1. A phyllosilicate sample with $\epsilon' = 4.74$, consistent with a sample that was dehydrated at 100 °C (Section 9.1.2) yields a critical thickness of ~ 16 m. The sample having experienced a water mass loss 8% below the control sample reduces the attenuation rate of the material such that SHARAD radar signals are capable of propagating through reasonably thick phyllosilicate layers. Further, a ϵ' decrease to 3.35 (Section 9.1.3) yields a massive increase in critical thickness to ~ 122 m. 10% water weight below the control sample is enough to allow nearly 50 times greater penetration depth than the control sample. Therefore, if the samples are as dehydrated as we made in the lab, they are not sufficiently attenuating to block the radar signal appreciably.

9.5 Saturation Results

9.5.1 Desiccation Process

Upon saturating the clays, we observe a mass increase of 100% from the powdered room humidity sample (See Table 9.6 for full list of masses and water percentages). Allowing the hydrated clay to desiccate in open air, we observe that even after a few hours, polygonal fracturing begins to occur (Fig. 9.21). After the first 24 hours, full

fracturing occurs. Around the edges of the patty, the sample has mostly reverted back to its original powder color. However, several polygons on the right side of the sample retain a darker complexion, which we attribute to maintaining a more saturated state (Fig. 9.22). The water weight percentage has fallen down to an 11.5% increase of the pre-saturation powdered sample. After 48 hours of desiccation, the fractures have all fully reverted in color to a non-saturated state (Fig. 9.23). The water weight percentage of the sample now lies at a $\sim 7\%$ increase from the pre-saturation powdered sample. Between 48 and 72 hours of desiccation, there are no visual changes observed, however the water weight percentage now lies at a $\sim 1\%$ increase from its original powdered mass (Fig. 9.24). After a full two weeks, the sample's water content has desiccated beyond the mass of the pre-saturation powder, lowering by $\sim 1\%$. We did not control for humidity fluctuations over the course of this experiment. Such a fluctuation may have been responsible for the $\sim 1\%$ water content reduction, although this is not certain.

	Sample Mass (g)	Water Gain From Original Powder Sample (%)
Powder Sample	59.4	NA
Fully Hydrated Sample	118.45	99.41
Day 1	66.25	11.53
Day 2	63.55	6.99
Day 3	60.15	1.26
2 Weeks	58.9	-0.84

TABLE 9.6: Water Percentages of Fully Hydrated Stx-1b Over the Course of 2 Weeks

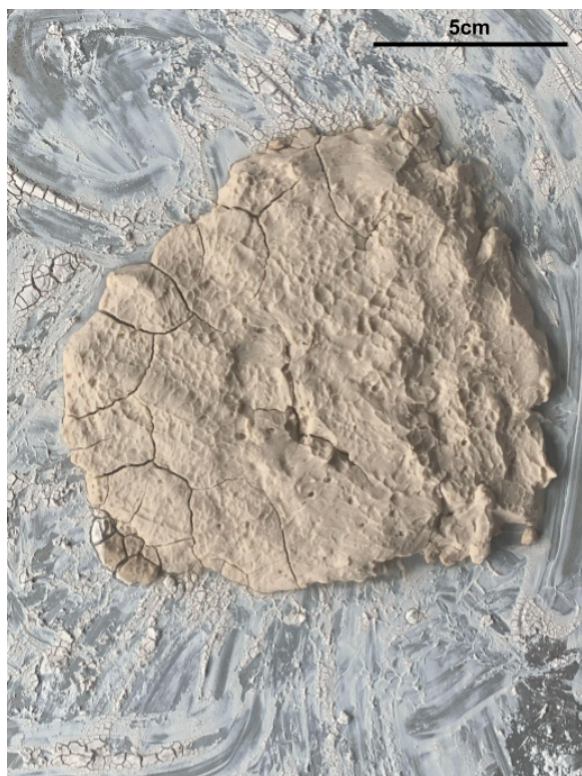


Fig. 9.21: Hydrated Stx-1b Patty After a Few Hours of Desiccation



Fig. 9.22: Hydrated Stx-1b Patty After One Day of Desiccation

9.5.2 Polygon Dimension Analysis

We find in our measurements, the larger polygons, on average, are ~ 2 cm wide, the largest being almost 3 cm. Their thicknesses range from 2 to 5 mm, with an average of ~ 3 mm. The smaller polygons on the outskirts of the main formation measured on average to be ~ 4 mm in width. The thicknesses measured an average of 0.6 mm (Table 9.7).

To compare these lab based fractures to the fracture dimensions observed on Mars that we present in Section 9.3.1.1, we calculate a scaling factor for each formation (Table 9.7). We additionally include the dimensions of polygons cited by El Maarry et al. (2014). These are cm scale polygons observed at dried lake beds in California. The scaling factor is a ratio of the polygon thickness to its width. We then plot the scaling factor by its width (Fig. 9.25). The trend of the data implies that there is a correlation between the thickness of the deposit and the size of its polygons. This also supports our hypothesis that the polygons we observe at Aurorae Planum have undergone desiccation from water table



Fig. 9.23: Hydrated Stx-1b Patty After Two Days of Desiccation

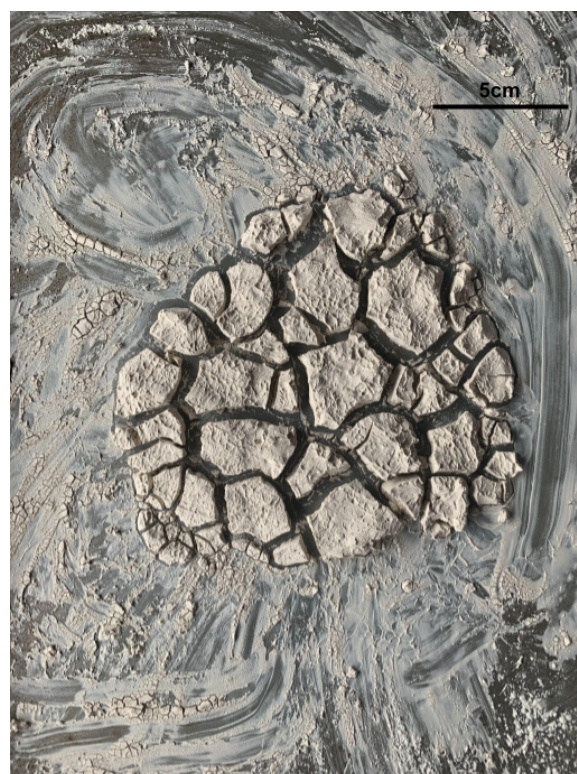


Fig. 9.24: Hydrated Stx-1b Patty After Three Days of Desiccation

retreat (Section 3.1).

It is possible that the polygons located at Aurorae Planum have undergone erosional processes which have altered their dimensions. We consider the amount of erosion experienced to not affect our correlation for two main reasons. The first is that these polygons have only been recently exhumed in the Amazonian epoch (Le Deit *et al.* 2010, Le Deit *et al.* 2012). Meaning that for a majority of their existence they have been covered by layers of dust and ash, shielded from erosional elements. The second reason is that aeolian erosion is an incredibly slow process. Some locations of Mars experience erosional rates of 0.03 mm per year (Golombek *et al.* 2006). For such large structures as these 10s of meters scale polygons, this rate is negligible, yielding a dimensional loss of < 1 mm over the span of the Amazonian.

	Average Polygon Width (m)	Average Polygon Thickness (m)	Scale Factor
Small Polygons	0.0037 ± 0.001	0.0006 ± 0.0004	0.16 ± 0.11
Large Polygons	0.0199 ± 0.0062	0.0031 ± 0.0011	0.16 ± 0.07
El Maarry et al. (2014) Polygons	0.2 ± 0.06	0.03 ± 0	0.21 ± 0.09

TABLE 9.7: Lab Measured Polygon Dimensions

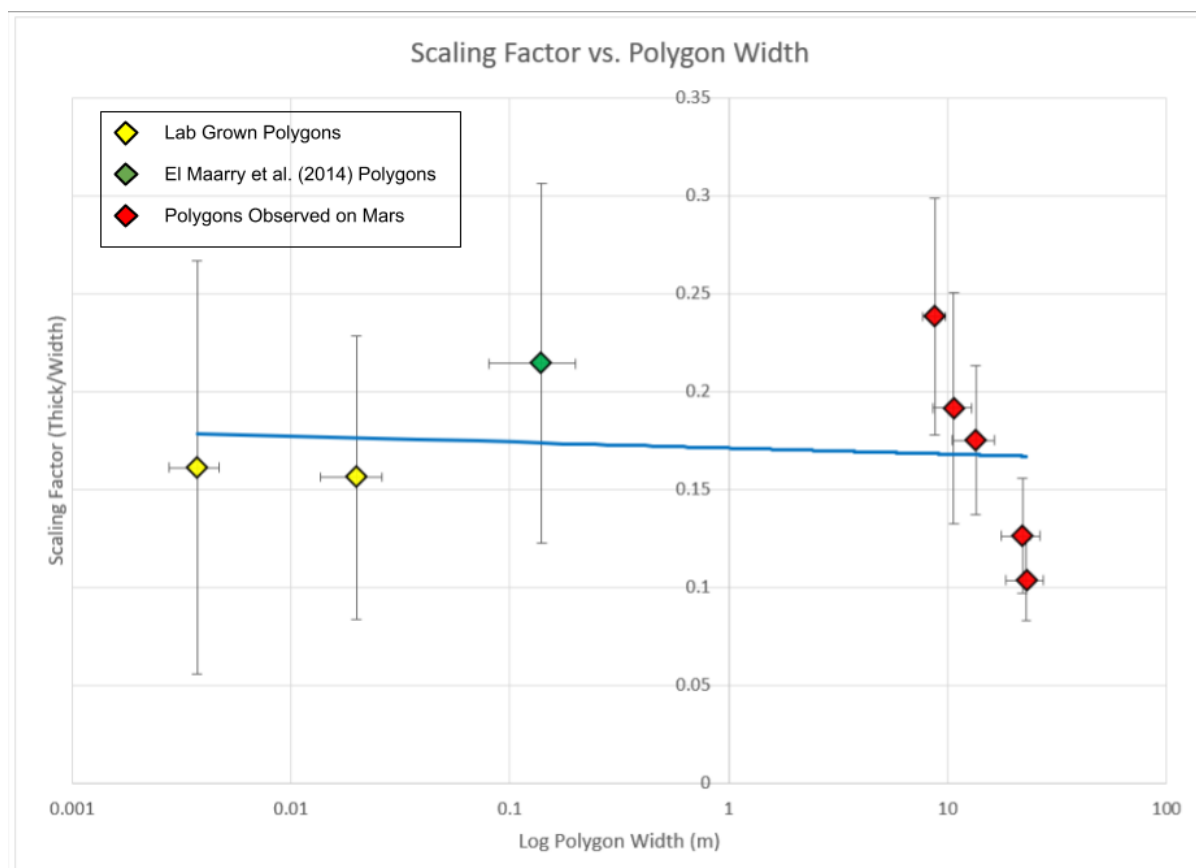


Fig. 9.25: Plot of Polygon Scaling Factor to Polygon Width

9.5.3 Vacuum Dehydration Results

Following the steps highlighted in Section 8.3, we leave a room humidity sample of stx-1b in a vacuum at ~ 5 Torr to dehydrate for two weeks. Over that span, the sample lost a water weight percentage of $\sim 4\%$ from its original room humidity weight. This is half of what we observed in our 100°C baked sample from Section 9.1.2. Over the period of those two weeks, the pressure did not remain stable. It had risen from 5 Tor to 83 Tor. We assume that if constant pressure was maintained, the water mass loss percentage would have been greater.

We had attempted to repeat the same process of dielectric measurement as had been conducted for the baked samples. However, clays, when removed from a vacuum rapidly

acquire humidity from the ambient air, gaining mass. In the time it took to pack the sample and prepare it for measurement, it had already readsorbed most of what water weight it had lost in vacuum.

10 South Polar Layered Deposit Research

The experiments conducted in this study have directly influenced and supported the research conducted in Smith et al. 2021. Specifically, the dielectric measurement methods described in Section 4 and the phyllosilicate hydration methods described in Section 8.1.

In 2018, a study had used MARSIS radar to observe what the authors interpreted to be a liquid water lake below the surface of the south polar cap of Mars (Orosei *et al.* 2018).

The problem with such an interpretation is that it would require an incredible amount of salt in the water in order to generate the reflections that were observed Smith *et al.* 2021.

This thesis study inspired an explanation that was far more credible. Frozen hydrated clay deposits.

As a subsidiary to the experiments conducted for this thesis study, we conducted dielectric experiments on hydrated stx-1b, in the same manner described in Section 4 for the dried clays. In order to do so, we hydrated samples by letting them sit in a steam bath, and then packed them into the airline for dielectric measurement. Further, the samples are cooled to ~ 230 K in order to measure the dielectric properties of the frozen hydrated clays. A final measurement is conducted using the saturation methods used in this study. The same process is followed for dielectric measurement. Both measuring at room temperature and then freezing at 230 K. The results of this study were able to successfully provide an alternate and more plausible explanation for bright reflections experienced below the South Polar Cap of Mars. Smith et al. (2021) is currently in the final stages of review for the Journal of Geophysical Research. The direct impact of this current thesis study to this paper supports the importance of the research conducted in this study.

11 Discussion

11.1 Desiccated Clays

In our dielectric lab experiments, we have shown that reducing the water weight percentage of a phyllosilicate sample, such as Ca-Montmorillonite, through baking drastically lowers its ϵ' and $\tan\delta$. In turn, these lowered dielectric values reduce the amount of attenuation experienced by radar signals travelling through the medium. In the case of the sample baked at 100 °C for 24 hours (Section 9.1.2), which experienced a water weight percentage reduction of $\sim 8\%$ from the room humidity control sample, a ϵ' and $\tan\delta$ of 4.74 and 0.15, respectively, will allow the transmission and reflection of SHARAD signals in a layer up to 16 m thick. As shown in Section 9.2, the deepest basal interface observed at Aurorae Planum with a ϵ' of ~ 5 , is ~ 15.6 m below the surface. A sample of Stx-1b at terrestrial humidity, such as the control measurement discussed in Section 9.1.1 that has a ϵ' of ~ 20 would attenuate SHARAD signals beyond a detectable signal through a layer ~ 2.5 m thick, which is around the thickness we measure the phyllosilicate layers to be. This implies that some degree of desiccation is necessary for even the thinnest deposits to provide the observed basal reflections.

The origin of this desiccation, we argue, is through the retreat of the water table, via evaporation, from remnant pools of a catastrophic flood from Morella crater. A clear correlation is noticed with the existence of polygonal fractures in these pooling locations, and the observed basal reflections. As we show in our experiments with Section 9.5.1, hydrated clays left without a continuous source of water will desiccate and form polygonal fracturing, as described by El-Maarry *et al.* 2015. The dimensions of these lab formed polygons scale to the dimensions of those we observe at Aurorae Planum, supporting our hypothesis of water table retreat formation in this region. Further, our experiments showed the potential of evaporative retreat desiccating the clays beyond their initial hydration state, albeit a $\sim 1\%$ water weight percentage loss at terrestrial humidity and atmospheric conditions, so it should be much greater on Mars after the flood recedes.

At Mars conditions, this decrease in water weight would be much higher, as we show with a terrestrial room humidity sample placed at 5 Torr for two weeks. While a leak in the chamber raised the pressure to 83 Torr, the desiccation experienced yielded a mass loss of 4% from the initial water weight percentage. This water weight loss is half of what was experienced by baking the sample at 100 °C for 24 hours. If the chamber was able to maintain vacuum at 5 Torr for the entire two week period, we assume the water weight loss percentage would be closer to that of the 100 °C baked sample, supporting the hypothesis that water table retreat is a significant enough mechanism to allow the transmission of SHARAD signals.

11.2 The Morella Outflow Event

We believe that the basins discussed in Section 1.1.2.1 play a key role in the timeline of the Morella Crater Outflow Event (Coleman *et al.* 2007, Komatsu *et al.* 2009, Coleman 2013). The shallow slope of the southern basin and the flat topography of the northern flatlands imply that these regions could have been subject to flooding as the initial breach of Morella Crater overwhelmed the immediate landscape with a deluge of water. Water, as a fluid, follows the path of least resistance, the path being towards these basins, as the direct east flow is overwhelmed because the channels had not yet formed.

We propose the process of the event followed as such:

- 1) First the pressurized groundwater begins to flow forth from Ganges Cavus, filling the crater with water (Coleman *et al.* 2007, Coleman 2013). (Fig. 11.1)
- 2) Reaching a critical point, the pressure of the crater lake breaches the eastern wall of the crater, flooding the surrounding plateau in the direction of Ganges Chasma to the east (Coleman *et al.* 2007, Coleman 2013). At the time of the flooding event, the surrounding plateau would have been relatively flat around 1700 to 2000 m in elevation with a slight trend downwards towards the east, consistent with what is observed with the majority of the rest of the plateau (Fig. 1.7). At the onset of the flood, and prior to the formation of Elaver Vallis, the waters would overwhelm this

terrain, with no direct direction to follow. This causes the flood to spread out in every direction; particularly into the northern flatlands and southern basin discussed in Section 1.1.2.1, with the bulk of the flow headed directly east. The flood waters headed north spills over the flatlands and into Ganges Chasma, while the flood waters filling the basin could have potential reached up to the rim of and spilled into Capri Chasma. The extent of which the plateau was flooded could have potentially reached across the entirety of Aurorae Planum, however this is unlikely due to a lack of evidence of flow in the region (Fig. 11.2).

- 3) Due to the shallow slope of the southern basin, and the near constant stream of water flooding from the crater, the water that rushed south begins to pool within that basin, unable to flow back in the wake of the constant pressure of the flow directly flowing south. The pressure of the eastern flow begins to excavate the beginnings of the primary and secondary channels (Fig. 1.6) as it carries away the surface regolith (Coleman *et al.* 2007, Coleman 2013) (Fig. 11.3).
- 4) As the water level in the crater recedes the power of the flood stream recedes. At a certain point between 1 and 1.7 days into the flood, the water level recedes to a point that the flooding stream recedes below 1600 m in elevation (Coleman 2013). All parts of the plateau above 1500 - 1600 m in elevation begin to drain. These locations include both parts of the secondary channel and the southern basin. As the southern basin is finally relieved and able to drain, it flows into the primary channel. The shallow, nearly flat grade of the basin implies that backflow into the primary channel will have a low flow rate. As it drains, the basin retreat channel we see on the modern surface is formed (Fig. 1.6). As the basin begins to drain, two sub-basins, one to the west and one to the south remain pooled. A basin forms in the northern flatlands as well, as the flat terrain allows no clear flow path for the flood waters (Fig. 11.4).
- 5) After 7.5 days have passed, the water level in Morella crater will have dropped to an elevation of 1500 m, below the elevation of the rim of the breach site (Coleman 2013). The remaining water remains pooled in the crater, left to evaporate over time. As with the Basin and the flatlands, this allows time for the sediments at the floor

of the crater to undergo chemical alteration, forming Fe/Mg phyllosilicates in the Olivine rich region (Gaudin *et al.* 2018)(Fig. 11.5).

- 6) Since there is no longer a readily available source of water to keep these lakes full, the pooled water begins to evaporate. As the water evaporates, the newly formed phyllosilicate deposits are left to desiccate in the temperate to sub-arid environment of Hesperian Valles Marineris. This desiccation process will leave the deposits to shrink and crack, forming polygonal fractures (Fig. 11.6).

We believe these events sufficiently provided an environment for these phyllosilicate deposits to form and then desiccate due to water table retreat.

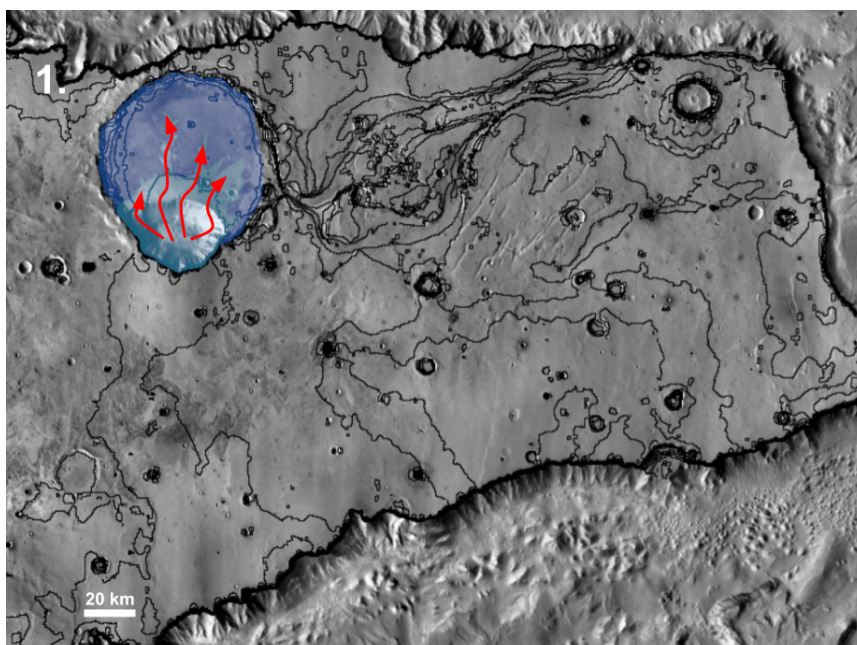


Fig. 11.1: Morella Outflow Event Step 1

Water surges forth from Ganges Cavus, filling Morella Crater. Light blue represents faster flow. The darker blue represents slowed flow or pooling water.

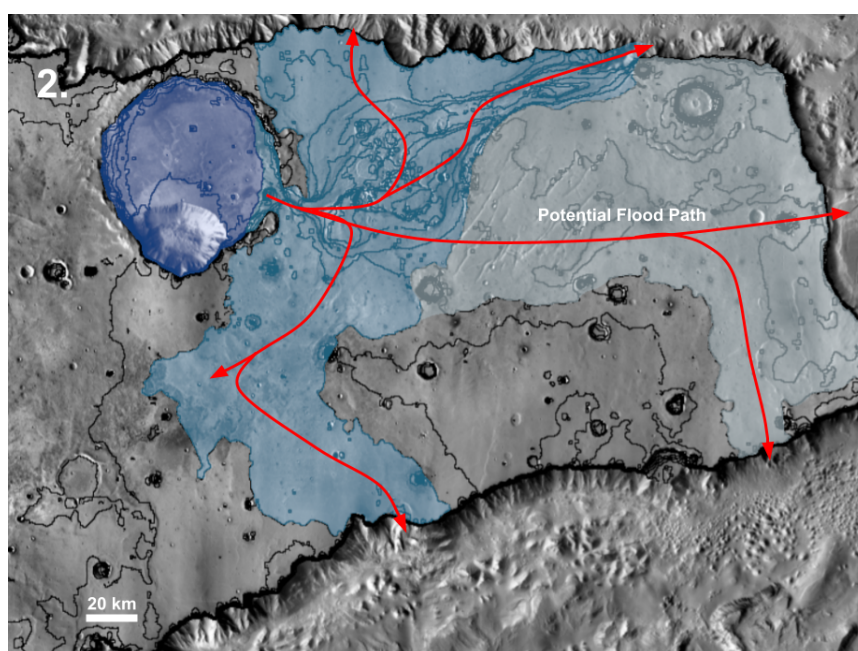


Fig. 11.2: Morella Outflow Event Step 2

The eastern wall of Morella crater breaches, unleashing a torrent of water flooding across the relatively flat plateau. The lighter region of the map represents a potential extent of the flood, however there is not enough evidence to support it. Light blue represents faster flow. The darker blue represents slowed flow or pooling water.

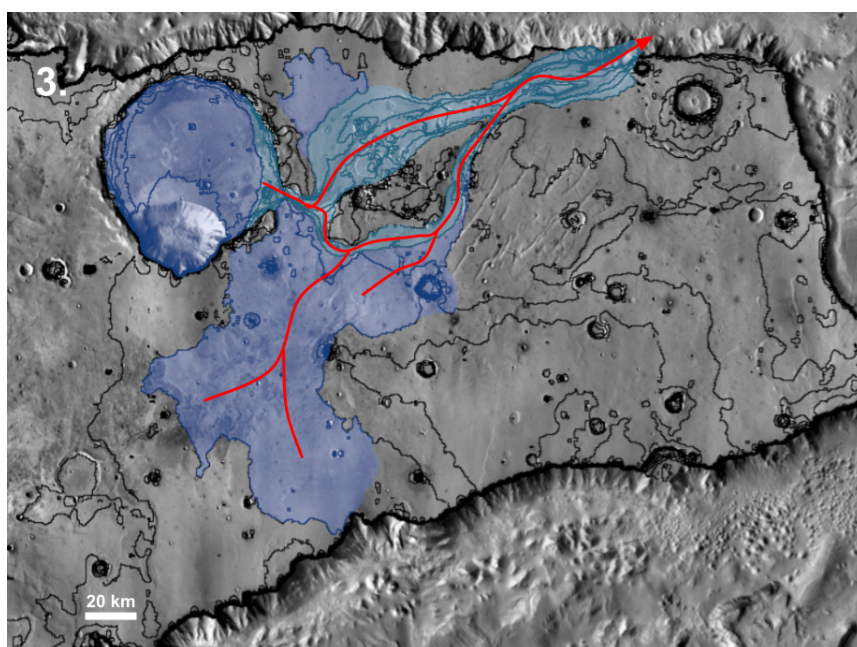


Fig. 11.3: Morella Outflow Event Step 3

Elaver Valles begins to form as the flood waters travel eastward across the plateau. Water pools in the southern basin, slowly flowing out due to the small slope of the area. Light blue represents faster flow. The darker blue represents slowed flow or pooling water.

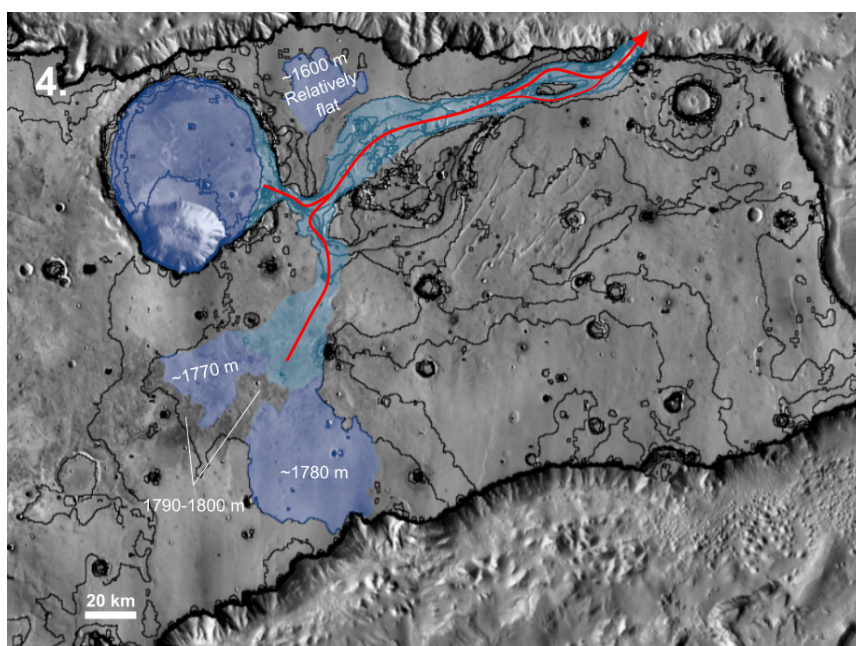


Fig. 11.4: Morella Outflow Event Step 4

The flood level recedes beyond 1600 m, draining the southern channel of Elaver Vallis and allowing the southern basin to begin to drain. This leaves behind two pooled basins in the south and a pooled environment at the northern flatlands. The darker blue represents slowed flow or pooling water

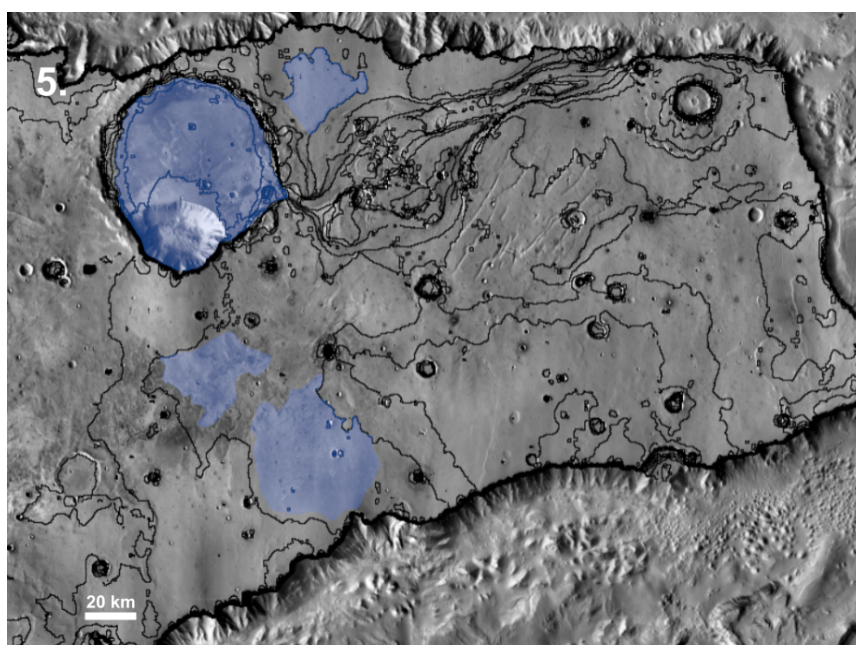


Fig. 11.5: Morella Outflow Event Step 5

The flood level recedes below the threshold of the breach, ceasing flow into Elaver Vallis. Water remains pooled in the crater, basins, and northern flatlands, providing an environment for phyllosilicate formation. The dark blue regions represent the pooled water locations.

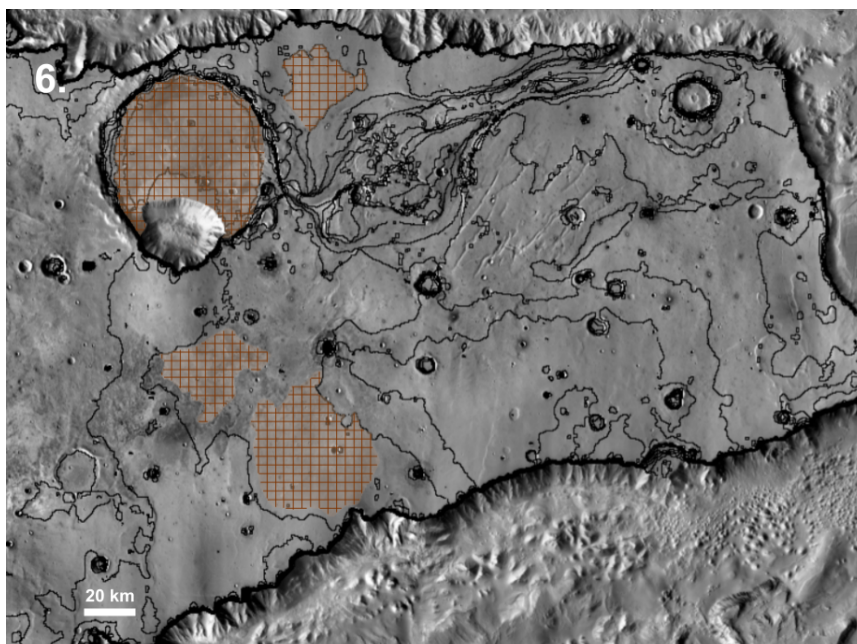


Fig. 11.6: Morella Outflow Event Step 6

The standing water evaporates, exposing the newly formed phyllosilicates to the elements, triggering desiccation that forms polygonal fracturing. The brown regions are the locations of polygonal fractures.

11.3 Thin Clays

The thicknesses of the clay deposits that we measure, at ~ 1.5 to ~ 3 m are far thinner than the maximum global thickness of 16 m predicted by Stillman & Grimm 2011. In addition to that, as we showed in Section 9.3.1.1, if it were the phyllosilicates causing reflections at such time delays, an unphysical permittivity would be required. Therefore, there needs to exist a layer underneath these thin deposits. We propose that this layer is the basaltic lava flows from the late Noachian that covered much of eastern Valles Marineris and make up the basis of the terrain over Aurorae Planum (Beyer & McEwen 2005, Tanaka 2014). There is an issue that successive lava flows shouldn't create a dielectric contrast. Therefore, something has to make the reflection. One possibility is that leached material settled at that depth, increasing the density, and giving the reflection. This evidence, along with the evidence for desiccation discussed in the previous two subsections supports our third hypothesis. It is clear that the phyllosilicate deposits formed from the Morella outflow event are thinner than based solely on SHARAD measurements and experienced a degree of desiccation sufficient enough to not fully attenuate SHARAD signals.

12 Conclusion

12.1 Conclusion

Radar is valuable for understanding the properties of surface and subsurface materials. In most cases, hydrated deposits like phyllosilicates make such observations a challenge due to their relatively high loss tangents; however, at Aurorae Planum, we are offered an opportunity to investigate this problem. In this study, we have investigated the mechanism behind observed radar reflections at the phyllosilicate rich plateau of Aurorae Planum, contrary to what is expected. We hypothesized that this contradiction is able to occur either because the phyllosilicates have desiccated due to water table retreat, rendering them with lowered loss tangents, or the phyllosilicate layers are not thick enough to affect or be seen by SHARAD signals. . . or a combination of both. We tested these hypotheses with a five step plan involving a combination of laboratory analog experiments and remotely sensed data analysis.

We performed dielectric measurements on terrestrially derived materials of the same composition as the Fe/Mg and Al clays located around Aurorae Planum. For these measurements, we adopted methods used by Boivin et al. (2018) to measure the signal transmitted through and reflected by the sample in a coaxial airline from 300 kHz to 1 GHz. Then we calculated the dielectric permittivity and loss tangent of the sample. In order to determine the bound water content of the deposits on Mars, we dehydrated samples at varying temperatures, and calculated their dielectric properties to match a level of dehydration that allows for full transmission of the layers observed in the SHARAD tracks. This has allowed us to constrain a water weight percentage of those phyllosilicates sufficiently low enough to allow SHARAD to observe the basal reflections.

In addition, we used SHARAD to map the extent of subsurface reflections and then cross-referenced them with CRISM and HiRISE data to expand past mapping of the deposits. The depth of the detections were identified in order to determine the true depth of the reflections. These results were compared to those of the laboratory experiments to confirm

whether desiccation alone is enough to account for this contradiction.

Through our experiments and data analysis, we have shown clearly that hydration state has a drastic effect on the permittivity and loss of a phyllosilicate material. This fact is a key component in the story of why the phyllosilicates of Aurorae Planum are penetrable by radar. We have found that after the megaflood of Morella crater, pooling water altered the sediments in key basins and flat regions, generating thin phyllosilicate deposits up to ~ 2.5 m thick, far thinner than the 16 m maximum predicted by Stillman & Grimm (2011). As the water retreated from the region, via evaporation, the newly formed hydrated phyllosilicates began to desiccate forming polygonal fractures, and losing bound water. In turn, the loss of water lowered the ϵ' and $\tan\delta$ of the material sufficiently enough that the attenuation rate for SHARAD radar allows full two way transmission. During the flood, the deposits were fully saturated. Although our experiments potentially have not reached full saturation, our results still imply that the deposits on Mars experienced a water weight percentage loss of $>>8\%$ to allow the full two way transmission of SHARAD radar. We see this as the case for all three regions highlighted within this study. Therefore it is clear that the phyllosilicate deposits of Aurorae Planum are thinner than previously expected, and have undergone a significant desiccation event, satisfying the conditions for our third hypothesis (Section 3.3).

12.2 Future Work

In the future, we would like to see our laboratory experiments repeated for different types of Al and Fe/Mg phyllosilicate analogs, such as saponite, nontronite, and vermiculite. We acknowledge that Ca-Montmorillonite is not the only potential phyllosilicate in these regions, so it would be important to cover all possibilities to confirm our hypothesis further. Additionally, we would like to develop a further method in which all steps of the lab experiments are conducted in vacuum at Mars pressures. This would resolve the problem that had occurred with our initial vacuum experiment detailed in Section 9.5.3.

It would be excellent to continue mapping polygonal fractures over Aurorae Planum with

further HiRISE images moving into the future. One of the biggest restricting factors on this analysis was the limited amount of HiRISE images over Aurorae Planum. Having more HiRISE data covering key parts of the plateau would greatly aid investigations.

And on a final note, continuing this whole investigation for more regions of Valles Marineris where there have been other hypothesized outflowing/megaflood events would prove beneficial. Finding more contradictory locations where we can observe and transmit through phyllosilicate deposits with radar will greatly aid in our understanding of phyllosilicates on Mars.

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