



Bulk composition of regolith fines on lunar crater floors: Initial investigation by LRO/Mini-RF

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ABSTRACT

Identifying polarimetric radar signatures of ice in smooth regolith fines on the floors of permanently shadowed lunar craters is hindered by uncertainties in their dielectric properties. We address this deficiency through polarimetric radar analysis of surface backscatter to derive the dielectric constant (ϵ'_r) of smooth, rock-free regolith fines covering brecciated crater floors observed by Mini-RF, which offer ideal locations for unambiguous retrieval of surface ϵ'_r from linear polarimetric scattering models and CPR analysis for volatile identification. Specifically, we select fines covering crater fills in north polar and equatorial regions to constrain the range of variability of ϵ'_r as a function of latitude and crater diameter, where we hypothesize that the latter is indicative of the excavation depth of these fines. Our observations suggest that there is measurable variability in the dielectric properties of fines on lunar crater floors as a function of crater size and potentially with impact excavation depth, suggesting that small craters <5-km in diameter have ϵ'_r ranging from 2.3-to-3, and large ones >5-km have higher values of ϵ'_r that range from 3-to-3.8. We find that the most plausible explanation for the observed variability of ϵ'_r of regolith fines on crater floors is mineralogical differences, suggesting an increase in metal abundance in the original excavated substrate with depth, i.e., in the uppermost kilometer of the lunar crust. Finally, we suggest that regolith fines on the floors of permanently shadowed craters <5 km in diameter are optimal targets for the unambiguous detection of water-ice enrichment using S-band radar observations.

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1. Introduction

Understanding volatile occurrence near the surface of the Moon and deeper in the interior provides crucial insights into its origin and evolution, as well as into the viability of using lunar volatiles as a potential resource for future human exploration. Of particular importance is how volatiles relate to the composition of the lunar interior, where the scientific consensus has shifted from a hydrous component of less than 1 ppb (e.g., Taylor et al., 2006) to as much as 100 ppm (e.g., Saal et al., 2008; Hauri et al., 2011; Milliken and Li, 2017; Greenwood et al., 2018)—a five-order increase in magnitude that has significant implications for early planetary accretion models with respect to the depletion and retention of volatiles

within rocky bodies in general (Elkins-Tanton, 2013; Greenwood et al., 2018).

The Clementine bistatic radar experiment reported finding evidence of ice in the vicinity of Shackleton crater (Nozette et al., 1996), whereas Earth-based Arecibo radar observations suggested no significant difference between the sunlit and permanently shadowed walls of the crater (Campbell et al., 2006). However, recent observations by the Moon Mineralogy Mapper (M^3) instrument aboard Chandrayaan-1 have provided spectral evidence that ~3.5% of lunar cold traps (permanently shadowed polar craters) bear significant ice content (i.e., ~30%) in their regolith (Li et al., 2018). This spectral evidence places strong emphasis on the importance of conducting new quantitative analyses of both orbital and Earth-based radar observations of the lunar poles to assess the geographical extent of such volatile occurrence.

In an attempt to reduce the ambiguities associated with radar observations of the lunar surface, two orbital synthetic aperture radars—Mini-RF aboard the Lunar Reconnaissance Orbiter (LRO) and Mini-SAR aboard Chandrayaan-1—have measured monostatic

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radar backscatter from the lunar surface with the primary purpose of detecting distinguishable polarimetric signatures of ice inclusions in the shallow lunar subsurface in shadowed polar areas (Spudis et al., 2009). Toward this end, constraining the distribution of dielectric properties across the lunar surface, and hence their role in radar surface scattering and subsurface penetration depth, is essential to reducing uncertainties associated with the identification and quantification of potential ice inclusions in the lunar regolith. While samples returned by the Apollo astronauts provided a unique opportunity to directly measure the electrical permittivity and magnetic permeability of lunar rocks and soils during the 1970s using different laboratory measurement techniques (Olhoeft and Strangway, 1975; Carrier et al., 1991), the employed methods were far from uniform or comprehensive—conducting measurements at different laboratories, using different techniques, and spread over a narrow range of frequencies, porosities and temperatures. Furthermore, all of the Apollo regolith samples were collected from the equatorial nearside of the Moon. As a consequence, the dielectric properties of the Moon's polar regions and farside remain poorly constrained, making it difficult to correlate existing laboratory-measured dielectric properties of lunar samples with geographical variation across the lunar surface, which in turn is needed to support the analysis of polar radar observations aimed at volatile detection.

Together, Mini-RF aboard LRO and Mini-SAR on Chandrayaan-1 provide unique opportunities to explore the Moon's radar properties, such as surface roughness and the dielectric properties of the lunar regolith, at both S- (2.38 GHz) and X- (7.14 GHz) bands in hybrid dual-polarization mode—i.e., transmitting circularly polarized radiowaves and receiving in two linear polarizations (horizontal H and vertical V) (Raney et al., 2011). Most efforts to detect water-ice using radar observations have targeted the walls of permanently shadowed craters due to their ideal thermal conditions for stable ice presence in the lunar shallow subsurface (e.g., Nozette et al., 1996; Stacy et al., 1997; Nozette et al., 2001). However, recent observations suggest that ice can also reside within the loose layer of regolith fines on the floors of craters (Zuber et al., 2012). We demonstrate in this study that these areas are better targets for ice detection by radar than those previously considered on crater walls, which remain ambiguous and controversial due to the uncertainties and complexities of both surface and subsurface scattering mechanisms in cratered terrains (Campbell et al., 2006; Campbell, 2012; Spudis et al., 2013).

In this study, we use monostatic H/V polarimetric linear backscatter ratios observed by LRO Mini-RF at S-band to estimate the dielectric variability of smooth regolith fines overlying crater fills in north polar and equatorial regions of the Moon. We define “H/V” as the ratio of horizontally-received (H) backscatter to vertically-received (V) backscatter that is measured by Mini-RF or Mini-SAR after transmitting left-hand circularly polarized (LCP) radar waves. Additionally, we utilize Mini-RF X-band and Chandrayaan-1 Mini-SAR S-band backscatter scenes to help identify smooth, rock-free areas on crater floors—since Mini-SAR images are acquired at a different incidence angle and therefore offer further validation of cm-dm surface roughness assessed from Mini-RF images. The selected sites, smooth regolith fines on crater floors, offer ideal locations for unambiguous retrieval of surface dielectric properties from linear polarimetric scattering models. Dielectric properties of the uppermost tens of cm to m of unconsolidated regolith fines covering crater fills are then plotted as a function of crater diameter to explore a first-order dielectric depth profile within the lunar subsurface. Observed values are compared to laboratory measurements of different lunar analog soils that have different iron and titanium concentrations, densities and ice enrichments in an attempt to provide insight on the bulk composition of investigated areas. Finally, implications

for the detectability of ice presence in the regolith fines covering crater fills are discussed for the ongoing Mini-RF experiment aboard LRO.

2. Polarimetric response of planetary surfaces

Both the Mini-RF and Mini-SAR experiments consist of hybrid radar systems that are able to transmit circularly polarized waves and receive in two orthogonally polarized channels, horizontal (H) and vertical (V). For a given pair of monostatic polarimetric scenes of the same area, the strength of the backscattered radar signal is mainly a function of the apparent slope, surface roughness and regolith dielectric properties at the surface (e.g., Campbell, 2002; Fa et al., 2011).

With respect to slope, the regolith fines covering the crater fills selected in this study are flat; 13 of the 15 equatorial crater fills have a root-mean-square height of $h_{\text{rms}} < 6$ m, which we calculate within a 200-m by 200-m grid using surface heights from the 59.2 m/pixel digital elevation model generated by Barker et al. (2015) from LRO's Lunar Orbiter Laser Altimeter observations, thereby removing slope from the parameters affecting radar backscatter.

Surface roughness, in turn, is characterized by the presence of surface scatterers that are comparable in size to the observing radar wavelength (i.e., centimeter- to meter-sized rocks for S- and X-band radar observations). To minimize ambiguity associated with retrieving the dielectric properties of regolith fines, we select areas within crater floors that appear smooth and rock-free on the surface at the cm-dm scale by identifying radar-dark zones in polarimetric scenes of crater floors by both Mini-RF and Mini-SAR (i.e., quasi-specularly reflecting and not including radar shadows), and also at the meter-scale by using rock abundance maps derived from the LRO Diviner Radiometer (Bandfield et al., 2011) along with optical scenes of central crater floors by the LRO Narrow- and Wide-Angle Camera (LROC NAC and WAC; Robinson et al., 2010).

An example of a typical smooth crater floor at the cm-dm scale considered in our study is shown in Fig. 1, which contains monostatic radar backscatter scenes of a 2.6-km diameter simple crater inside Amundsen crater (near the lunar south pole) at H and V polarizations for both Mini-SAR and Mini-RF at S-band and X-band, respectively. The similarity of the crater floor's radar backscatter between the H and V polarizations suggests an arbitrarily rough surface (Campbell et al., 1993; Campbell, 2002, 2009). Furthermore, the crater floor appears radar-dark at both S- and X-band frequencies, suggesting that the surface of this crater fill has measurable smooth areas from the cm-dm scale. We also note that backscatter SNR is constant across the scene at about -35 dB for S-band (-28 dB for X-band) baseline resolution, and approximately -28 dB for S-band (-21 dB for X-band) zoom resolution.

When selecting each site in this study, we have followed the same process of comparing the H and V polarimetric backscatter return in S-band with X-band to ensure cm-dm smoothness. The H and V backscatter returns are normalized to a constant incidence angle by dividing the data by an appropriate scattering model for both X and S bands, i.e., using the angle-dependent backscatter models computed by Thompson et al. (2011), Fig. 3 therein. The detailed radargrammetry and normalization of the Mini-RF and Mini-SAR scenes are described by Kirk et al. (2010). Each scene has an improved ~60-m resolution after range-radiometric correction—noting that the Mini-SAR scenes used in this study were acquired between November 2008 and 19 May 2009, when Chandrayaan-1 was orbiting the Moon at its lowest altitude of 100 km.

Next, we verify meter-scale smoothness of a given central crater floor using the map of rock abundances developed by Bandfield et al. (2011) who used thermal observations by Diviner to derive rock abundances across the Moon, and found that crater floors

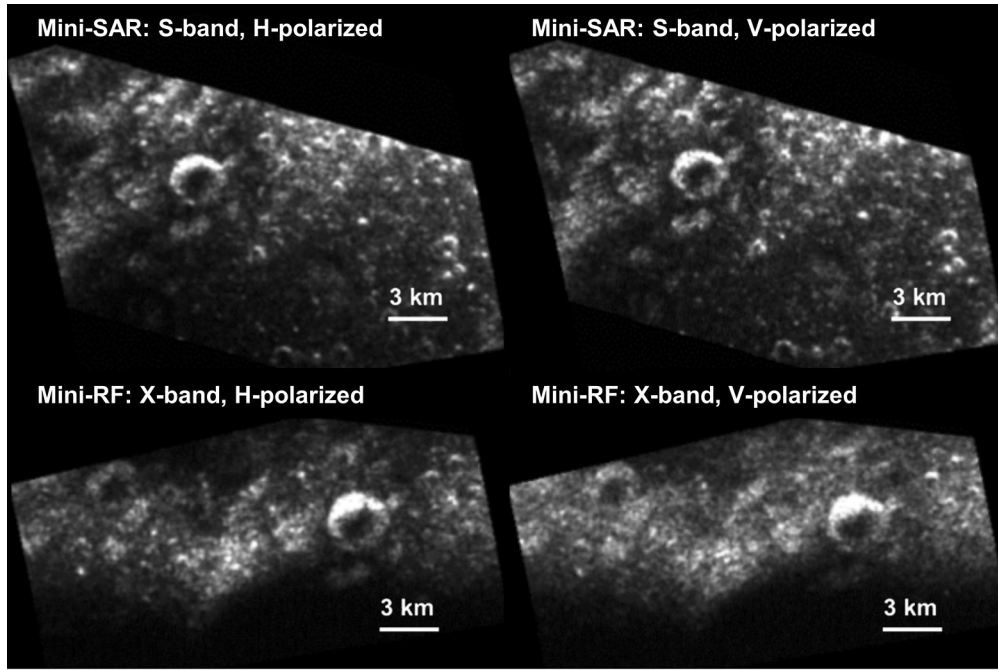


Fig. 1. Linearly polarized H and V radar backscatter scenes at ~ 60 -m/pixel resolution of a 2.6-km-diameter crater inside Amundsen crater near the south pole, acquired at S-band by Mini-SAR (top) and X-band by Mini-RF (bottom). Radar illumination is coming from the bottom right. The central crater fill appears radar dark in all four scenes, suggesting that the radar properties of regolith fines on crater floors are non-dispersive over S- to X-band frequencies, and that H and V scenes exhibit similarly weak backscatter return due to the presence of a rock-poor layer of lunar fines with arbitrary roughness.

typically contain no more than a few percent of boulders $\gtrsim 1$ m diameter with the exception of young craters, which have not undergone sufficient gardening to develop a rock-free mantling layer of regolith (e.g., Hörz et al., 1991). Bandfield et al. (2011) also extrapolated rock abundances to smaller sizes applicable to radar wavelengths, and suggested that for older small craters $\lesssim 15$ km in diameter, the observed lunar-night temperatures of crater floors are consistent with the presence of rock-free regolith fines that are heated by radiance from the surrounding crater walls.

Finally, we confirm the occurrence of measurable areas of smooth, rock-free regolith fines on the crater floor by using high-resolution optical scenes acquired by LROC (Robinson et al., 2010), as shown in Fig. 2 for four different craters considered in this study. Hence, the surface of crater fills in this study can be safely considered smooth at the scale of centimeters to meters, such that radar backscatter from the selected regolith fines is mainly a function of their dielectric properties as suggested by the Campbell et al. (2002) scattering model.

As radar scattering from arbitrarily rough surfaces like that of the Moon typically produces a similar response in H and V polarizations (Campbell et al., 1993; Campbell, 2002, 2009), a comparison between the backscattered return from both H and V polarizations therefore presents a valuable tool for understanding the dielectric properties at the observing radar frequencies—S- and X-band for Mini-RF, and S-band for Mini-SAR. Historically, circular polarization ratio (CPR) observations have been used for Earth-based radar observations of the Moon since they remove the need for ionospheric corrections. Yet for monostatic lunar orbital observations such as those by LRO and Chandrayaan-1, such corrections are unnecessary. In addition, linear polarizations can provide a more quantitative approach to understanding the surface's radar properties (i.e., dielectric and textural properties).

Campbell et al. (2002) suggest a dielectric inversion model for rock-poor mantling dust based on the normalized ratio between the H and V backscattering coefficients, representing the uppermost unconsolidated layer of lunar regolith fines in our model, which can range from a few centimeters to a few tens of centime-

ters deep on the crater floors targeted in our study (e.g., Carrier et al., 1991; Hayne et al., 2017). For a rock-poor layer of lunar regolith fines (i.e., containing no significant population of rocks larger than one-tenth of the radar wavelength λ), radar echo strength is comprised of only surface and subsurface returns as:

$$\sigma_{HH}^0 = \sigma_{HH_sur}^0 + AT_H^2 \sigma_{HH_sub}^0 \quad (1a)$$

$$\sigma_{VV}^0 = \sigma_{VV_sur}^0 + AT_V^2 \sigma_{VV_sub}^0 \quad (1b)$$

where $\sigma_{HH_sur}^0$ and $\sigma_{VV_sur}^0$ are the surface backscattering coefficients of the HH and VV polarizations; $\sigma_{HH_sub}^0$ and $\sigma_{VV_sub}^0$ are the subsurface backscattering coefficients of HH and VV polarizations; and A is the attenuation factor assumed equal for the HH and VV polarizations. T_H and T_V are the Fresnel power transmission coefficients for H and V polarization as follows:

$$T_H = \frac{4 \cos \phi \sqrt{\epsilon_r' - \sin^2 \phi}}{\left(\cos \phi + \sqrt{\epsilon_r' - \sin^2 \phi} \right)^2} \quad (2a)$$

$$T_V = \frac{4 \epsilon_r' \cos \phi \sqrt{\epsilon_r' - \sin^2 \phi}}{\left(\epsilon_r' \cos \phi + \sqrt{\epsilon_r' - \sin^2 \phi} \right)^2} \quad (2b)$$

where ϕ is the incidence angle, and ϵ_r' is the real part of the dielectric constant (hereafter simply referred to as the dielectric constant) of regolith fines.

The above model is also applicable to the case of a deep dust layer containing suspended rock inclusions with diameters $\geq \lambda/10$ in size ($\gtrsim 1$ cm for S-band), since radar scattering from discrete buried fragments typically produce similar HH and VV returns like the rough substrate described in the above simple two-layer model (Campbell et al., 2002). Hence, whether for a flat, smooth surface layer of rock-poor regolith fines overlying a rough consolidated

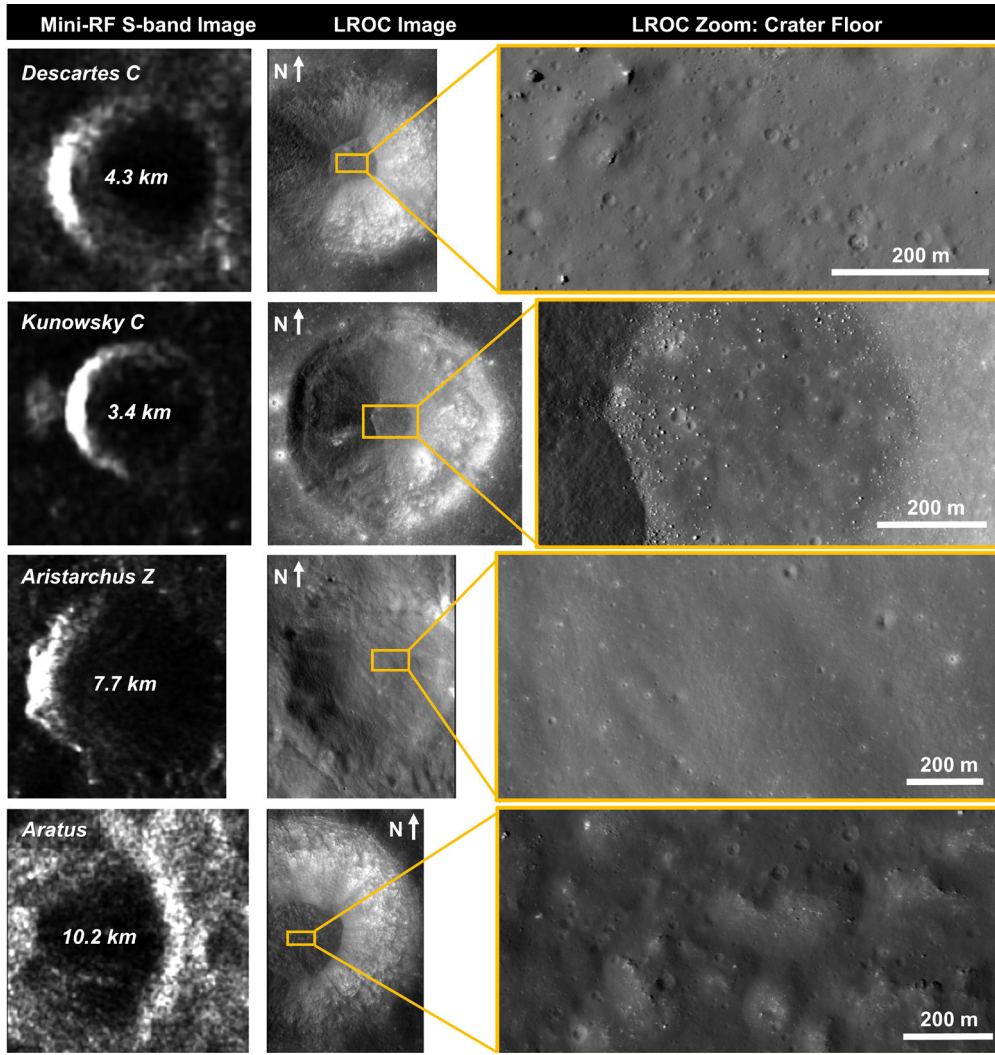


Fig. 2. LRO Mini-RF radar scenes (~ 60 -m/pixel resolution) of four crater fills and their corresponding LROC high-resolution scenes showing the meter-scale smoothness and tens-of-meters-scale flatness of crater floors. The resolution of the LROC scene of Descartes C is 0.7 m/pixel; Kunowsky C, 1.0 m/pixel; Aristarchus Z, 1.5 m/pixel; and Aratus, 1.4 m/pixel.

subsurface or overlying a layer of dust containing buried rocks with diameters $\geq \lambda/10$ —both of which are applicable hypotheses for the uppermost layer overlying crater floors considered in this study that is a few centimeters to a few tens of centimeters in depth (e.g., Carrier et al., 1991; Hayne et al., 2017)—we can assume that $\sigma_{HH_sub}^0 = \sigma_{VV_sub}^0$, and that $\sigma_{HH_surf}^0$ and $\sigma_{VV_surf}^0$ are negligible (Campbell et al., 2002). Then the ratio of radar backscattering coefficients between H and V can be expressed as:

$$\frac{\sigma_{HH}^0}{\sigma_{VV}^0} = \frac{T_H^2}{T_V^2} = \left[\frac{\varepsilon_r' \cos \phi + \sqrt{\varepsilon_r' - \sin^2 \phi}}{\sqrt{\varepsilon_r'} (\cos \phi + \sqrt{\varepsilon_r' - \sin^2 \phi})} \right]^4 \quad (3)$$

As the H/V ratio is directly obtainable from radiometric analysis of Mini-RF and Mini-SAR scenes, and the angle of incidence is specified for each measurement, the only remaining variable in equation (3) is the dielectric constant ε_r' , which can be obtained for a given surface from the corresponding Mini-RF or Mini-SAR polarimetric scene.

Fig. 3 shows a plot of the predicted H/V ratio from equation (3) as a function of the dielectric constant of regolith fines for incidence angles of 35° and 49° , which are the nominal look angles for Mini-SAR aboard Chandrayaan-1 and Mini-RF aboard LRO, respectively.

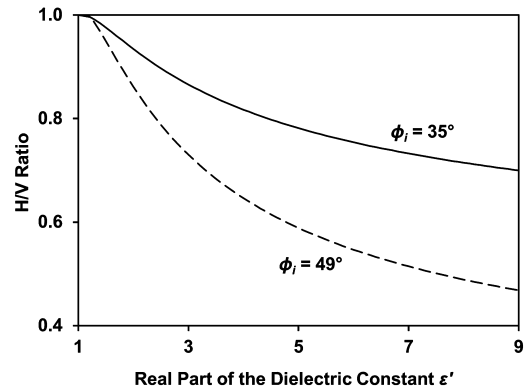


Fig. 3. Plot of H/V ratio from equation (3) as a function of surface dielectric constant at nominal look angles (incidence angles) of 35° and 49° for monostatic Mini-SAR and Mini-RF observations, respectively.

tively. For a given measured H/V ratio, equation (3) can therefore be applied to estimate the dielectric properties directly, where H/V ratios measured by Mini-RF or Mini-SAR are predicted to decrease with increasing dielectric constant of the regolith fines. The applicability of our results is therefore confined to the layer of unconsolidated regolith fines in specific selected areas inside the crater

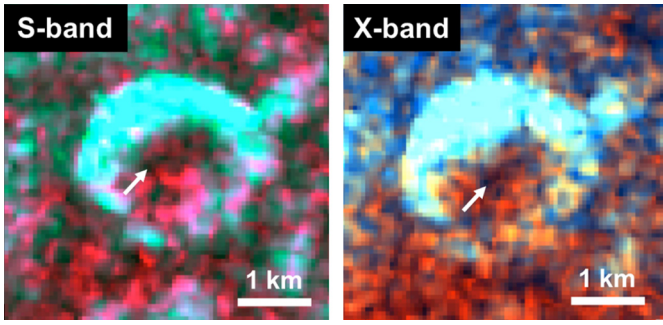


Fig. 4. S-band (left) and X-band (right) 3-channel color-composite polarimetric radar scenes of the crater from Fig. 1, where Red = H/V, Green = H, and Blue = V. The dark pixels identified by the white arrows represent smooth, rock-free areas that enable the use of the dielectric inversion algorithm in equation (3) for regolith fines covering the brecciated crater fill.

where the surface is flat and smooth with no concentrations of rocks exposed at the surface.

We next confirm that S-band penetration depths are sufficient to apply the Campbell et al. (2002) model to each of our sites when taking into account the attenuation of regolith fines associated with Fe and Ti metal abundance, which have been measured by the Lunar Prospector mission in the uppermost meter of regolith (Prettyman et al., 2006). We estimate S-band penetration depths using the model of Fa and Wiczorek (2012) assuming a regolith porosity of 45%, and find that depths range from ~4–7 m in our targeted sites. Such penetration depths are sufficient for the unconsolidated layer of rock-free regolith fines overlying crater floors, which constitute the targets of our study. The above radar analysis is applicable to these regolith fines on crater floors, and not to the regolith outside crater floors, where scattering properties may differ from the applicability of this two-layer model.

We only consider simple craters in this study (i.e., 1–20 km in diameter) as they are characterized by the occurrence of ~100-m sized areas of flat, smooth regolith fines overlying brecciated crater fills, providing applicable conditions for the Campbell et al. (2002) scattering model.

3. Results and analysis

Fig. 4 shows the 2.6-km crater inside Amundsen crater in two color-composite scenes, one for S-band and one for X-band from Mini-RF, recalling that the S-band scenes are used to retrieve the dielectric constant of regolith fines, while X-band scenes are used to verify that the surface and uppermost centimeters of regolith fines are smooth and rock-free at cm-dm scales. Each composite scene consists of the H/V polarimetric ratio (Red), H-received backscatter (Green) and V-received backscatter (Blue), where the difference between the S- and X-band composites vary as the amplitude changes between surface-scattering versus volume-scattering dominated mechanisms. For instance, the radar-bright region on the crater's northern wall is significantly brighter and wider in X-band than in S-band, suggesting stronger surface scattering that may be associated with surficial debris flow down the slope. In both S- and X-band, the southern crater wall is darker since less energy is reflected back to the transceiver due to surface tilt away from the incoming radar beam. Within the central crater fill, we select dark areas that are largely rock-free at the surface and filled with smooth regolith fines to enable the use of the dielectric inversion algorithm in equation (3). The H/V ratio in these dark areas at S-band ranges from 0.73 at the center of the fill to 0.82 toward the edges, corresponding to $\epsilon'_r = 5.44$ at the center to $\epsilon'_r = 3.62$ near the crater's walls as derived from equation (3), suggesting a radial decrease of ~40% in the H/V ratio outward from the crater fill center. In Table 1, these radial dielectric variations

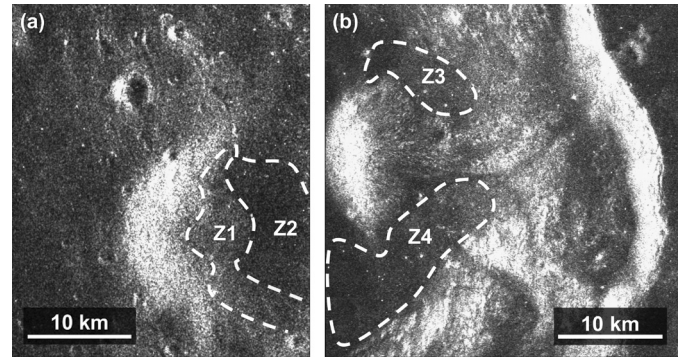


Fig. 5. Heterogeneity of radar backscatter observed within different zones of (a) a simple crater as compared to (b) a complex crater. Each scene was acquired in S-band by Mini-RF. Backscatter scene (a) shows a north polar crater at 82°N with radar illumination coming from the right. Backscatter scene (b) shows a crater in the southern hemisphere at 53°S with radar illumination coming from the left.

across the radar-dark, rock-free layer of regolith fines covering different crater fills are described by $\Delta\epsilon'_r$, which quantifies the deviation from the lowest value $\langle\epsilon'_r\rangle_{\min}$ measured on the crater fill.

Next, we examine the distribution of radar scattering properties across the floor of two craters of different morphological types: (1) a 15-km diameter simple crater near the north pole (Fig. 5a) and (2) a 50-km diameter complex crater in the southern hemisphere at 53°S (Fig. 5b). The simple crater in Fig. 5a is illuminated by radar from the right, revealing a radar-bright crater wall to the left, a radar-dark crater wall to the right (since it faces away from the source of radar illumination; labeled Z2) and a zone of intermediate radar brightness (Z1) that includes the central fill of the crater and is calculated to have $\epsilon'_r = 3.7$. By contrast, the 50-km complex crater in Fig. 5b shows a much more heterogeneous distribution of radar scattering properties within the crater basin. Radar illumination is coming from the left side of the scene, revealing a narrow, radar-bright crater wall on the right, and two relatively radar-dark zones on the crater floor (Z3 and Z4), where Z3 is calculated to have $\epsilon'_r = 2.8$, and Z4 has $\epsilon'_r = 2.2$, showing the dielectric heterogeneity of complex crater fills. To minimize the ambiguity associated with this complex distribution of dielectric properties within large craters, we confine this study to simple craters (i.e., $\lesssim 20$ km diameter; Pike (1977)).

To accurately retrieve the dielectric constant of lunar regolith fills on crater floors, we select a two-by-two pixel area (at a resolution of ~60 m/pixel, hence covering a square grid of ~120 m by 120 m) within the darkest area on the crater floor. This selection window in the radar backscatter scene ensures that neither the rims, walls, rocks, small impacts, nor radar shadowed parts of the crater are sampled when performing the polarimetric scattering analysis for our dielectric inversion. Expanding this window would result in the inclusion of potentially rougher terrain (such as blocky debris accumulating at the base of the crater walls and pixel-sized craters), and hence violate the applicability of our inversion model, yielding unrealistic values of ϵ'_r .

Table 1 summarizes the inverted dielectric properties at S-band of regolith fines on the floors of simple craters analyzed in this study, which includes 21 north polar craters and 15 equatorial ones. The corresponding S-band H/V Mini-RF scenes of each crater are given in Fig. 6. The dielectric values reported in Table 1 are the ones retrieved from the most central part of each radar-dark area, closest to the crater center. The increase in these values for the dark areas closer to the crater walls are also listed but we consider this increase to be a result of the thinning of the layer of regolith fines on crater floors (i.e., to less than one wavelength) as it approaches the crater walls. In this thin-layer regime, the application of the dielectric inversion from polarimetric scattering analysis is

Table 1

Dielectric constant of regolith fines on crater floors as inverted from linearly polarized scenes acquired by Mini-RF aboard LRO at S-band.

Orbit no.	Mini-RF scene # in Fig. 6	Pixel location		Diameter (km)	$\langle \varepsilon_r' \rangle_{\min}$	$\Delta \varepsilon_r'$	Latitude (°N)	Longitude (°E)	Crater name
		Line	Sample						
North Polar Craters									
1302	A1	185	445	16.5	3.40	1.94	80.25	-50.75	Mouchez M
1302	A2	145	5000	5.7	3.24	1.87	87.75	16.35	
1302	A3	115	5275	4.2	3.26	1.90	87.71	30.21	
1306	A4	180	5035	6.2	3.52	1.88	87.76	16.21	Sylvester N
1306	A5	250	940	2.4	2.27	1.14	81.32	-53.82	
1324	A6	165	1635	19.2	3.43	1.96	82.27	-69.26	
1324	B1	215	4390	5.3	3.19	1.84	87.05	-36.52	
1329	B2	190	280	4.6	3.12	1.75	78.07	-81.31	
1329	B3	265	535	8.8	3.01	1.77	78.59	-81.48	
1340	B4	260	1815	5.4	3.33	1.86	78.63	-92.87	
1340	B5	155	2975	4.8	2.74	1.64	80.83	-88.72	
1341	B6	135	1335	4.5	3.00	1.99	77.50	-94.24	
1341	C1	160	4020	5.4	3.29	1.94	82.72	-86.42	
1353	C2	190	3960	4.2	2.61	1.45	81.42	-105.17	Poinsot K
1451	C3	100	3650	7.8	3.36	1.98	87.05	-86.48	
1600	C4	140	2040	6.3	3.26	1.85	88.33	36.77	
1702	C5	150	6580	4.8	3.44	1.92	79.77	31.78	
1597	C6	130	1130	11.4	3.04	1.84	87.11	8.21	
1861	D1	240	6830	10.2	3.11	1.83	77.79	-138.11	
1866	D2	230	5185	15.0	3.42	1.98	76.84	-142.28	
1884	D3	200	2720	13.6	3.80	2.05	84.60	-172.47	
Equatorial Craters									
0880	E1	180	572	3.3	2.90	1.82	-4.77	33.11	inside Isidorus B
0880	E2	190	2700	6.6	3.08	1.77	-0.53	33.02	Censorinus A
1726	E3	160	3200	3.8	2.94	1.61	-11.41	16.36	Descartes C
1737	E4	130	1280	8.6	3.12	1.88	27.19	4.60	Santos Dumont
1737	E5	100	3380	10.6	3.35	1.91	22.97	4.49	Aratus
1771	E6	170	1240	3.0	2.48	1.11	-0.44	-32.46	Kunowsky C
1771	F1	200	1400	2.5	2.50	1.08	-0.55	-32.35	
1771	F2	165	2050	2.7	2.77	1.53	-1.85	-32.41	Aristarchus Z
1786	F3	165	2485	7.5	2.65	1.57	25.49	-48.49	
1801	F4	220	485	4.1	3.29	1.85	-20.85	-64.30	
1801	F5	150	650	5.0	3.26	1.80	-21.18	-64.52	
1801	G1	120	5010	51.8	3.24	1.84	-29.88	65.12	Lagrange C
1812	G2	145	175	12.0	3.43	1.97	11.18	-76.30	Cardanus C
1831	G3	195	1465	7.2	3.34	1.90	-27.14	-97	
1893	G4	185	935	5.6	3.31	1.86	27.19	-164	

compromised by significant errors >10%. Another source of error as the regolith fines approach the base of crater walls is the potential presence of small debris and boulders that originate from the crater walls, as they can act as discrete reflectors compromising the dielectric inversion, such as the ones shown in Fig. 2 for crater Kunowsky C near the crater walls. This provides additional support for the use of a confined two-by-two-pixel area in the center most part of the investigated crater floor to carry out our dielectric inversion.

In Fig. 7, we plot the surface dielectric constant of crater fills as a function of crater diameter, and find that ϵ'_r sharply increases with increasing crater diameter between 2 and 5 km, reaching a maximum at ~ 3.3 for craters $\gtrsim 5$ -8 km in diameter. The error bars shown in this plot are $\sim 10\%$ of the dielectric value associated with the most central part of the thin layer of regolith fines covering the crater floor, which arise from instrumentation and processing errors associated with radiometric calibration and retrieval of the H and V linear backscatter components (Raney et al., 2011) that are used as input for equation (3).

In addition, it should be noted that Carter et al. (2017) discovered that Mini-RF's onboard data compression algorithm applied a non-reversible, non-linear gain to backscatter power received by Mini-RF's S- and X-band antennas in both baseline and zoom modes. The effect on our results is that different gains were applied to the power received in the H-polarized versus V-polarized receiver channels for the same scene. Gain differences are particularly pronounced in sites with low backscatter <35 dB such as those selected in this study (Carter et al., 2017). Without the abil-

ity to directly quantify this radiometric error (Carter et al., 2017), we minimize its effects by having taken the linear ratio of H and V backscatter, by averaging these ratios over four different pixels within a given site, and also by measuring this averaged H/V ratio over a sufficiently large sample size of 36 different craters. As a consequence, observed variability in the dielectric properties of regolith fines as a function of crater size cannot be attributed to radiometric calibration errors. We have also compared each radar-dark site on a crater floor within a Mini-RF S-band scene to images acquired by Chandrayaan-1 Mini-SAR (Fig. 1) to confirm the occurrence of low H/V ratios within each site.

4. Implications for volatile detection in lunar craters using radar methods

For a specific observation geometry, two main factors control the ability to assess volatile occurrence in permanently shadowed craters at the lunar poles using polarimetric ratios from SAR imaging: (1) surface roughness and (2) their dielectric properties. We first find that the layer of regolith fines covering the brecciated fills of simple craters contain measurable areas (i.e., ~ 100 -m sized) that are rock-free and smooth at the cm-m scale. Secondly, we find that the dielectric properties of lunar regolith fines covering crater fills are not characterized by a single dielectric constant, but vary with the size of the crater as shown in Fig. 7. It is important to note that the dielectric constants used in this plot pertain to the values measured in the most central parts of the crater floor, i.e., away from any debris that comes from the walls. Subsequently, we

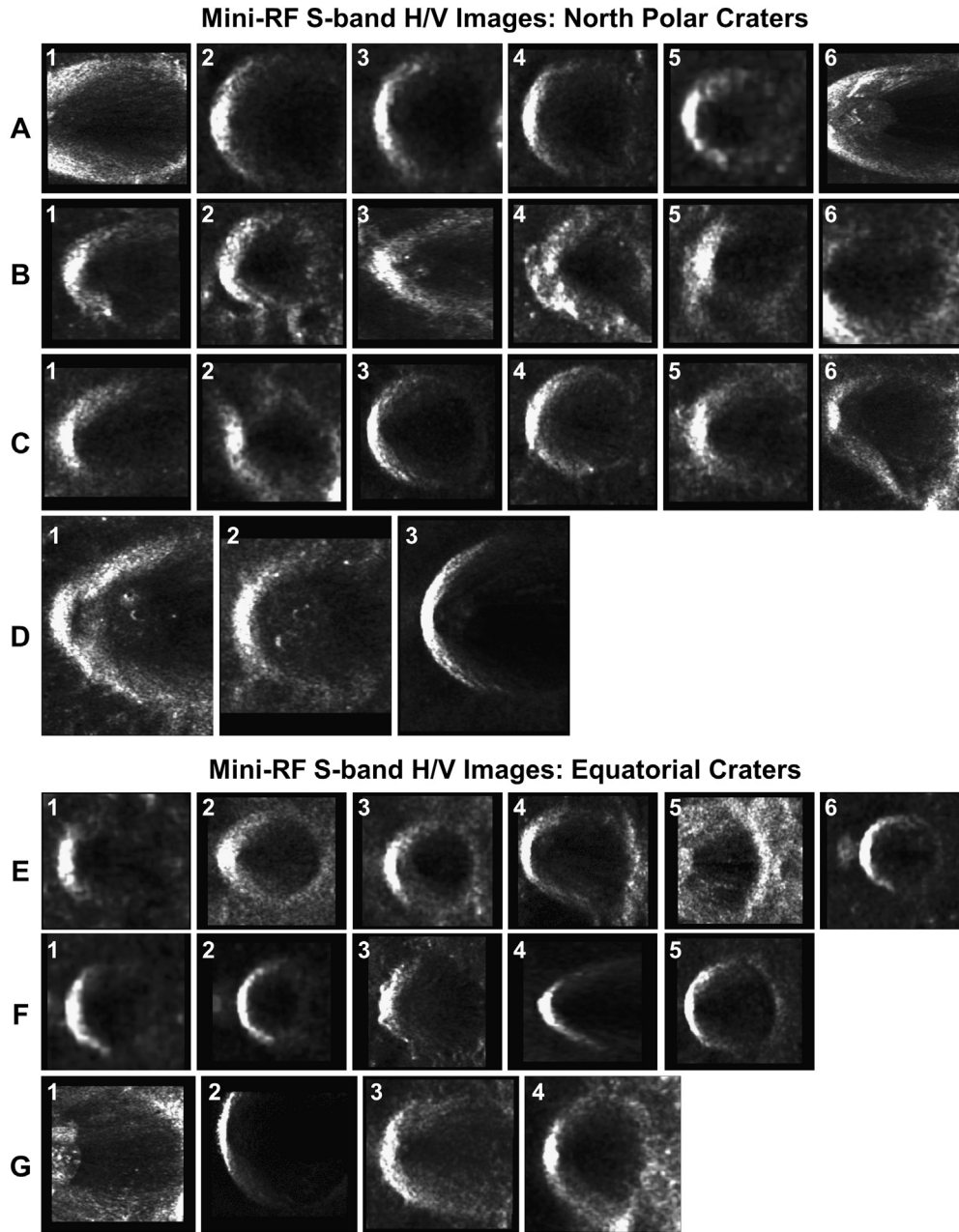


Fig. 6. LRO Mini-RF S-band H/V radar scenes of regolith fines overlying crater fills selected for this study (details provided in Table 1).

can hypothesize that the central layer of regolith fines overlying the brecciated fill arise from the initial excavation of the impact for the craters considered in this study (i.e., fallback ejecta)—where excavation depth is $\sim 1/10$ of the transient crater diameter (Melosh, 1989), and the transient crater diameter, in turn, is $\sim 85\%$ of the apparent crater diameter (Croft, 1985). We also recognize that in other craters, regolith fines can originate from crater wall debris flows or pyroclastics, along with other depositional mechanisms (e.g., Melosh, 1989; Gustafson et al., 2012; Bennett et al., 2016).

The dielectric properties of regolith fines on crater floors can be a function of density, FeO and TiO₂ abundance (herein also referred to as metal abundance) and volatile content. In what comes next, we explore the implications of our results pertaining to the relationship between crater size and the dielectric constant of the regolith fines covering its floor in terms of three potential drivers.

4.1. Density variability of regolith fines on crater floors

First we test the hypothesis that the observed variability of ϵ'_r is associated with increasing density of the regolith fines on crater floors with increasing crater size. For latitudes between $\pm 70^\circ$, Hayne et al. (2017) have generated a lunar soil compaction map at $128 \text{ pixel deg}^{-1}$ resolution using infrared data from Diviner aboard LRO. They apply a 1D heat-transfer model to the first meter of lunar regolith and vary the vertical profile of soil density, thermal conductivity and heat capacity to match the surface's night-to-day temperature fluctuations observed by Diviner (Hayne et al., 2017). Soil compaction within the first meter is then estimated by (1) setting the density of the topmost layer of regolith to $1,100 \text{ kg m}^{-3}$ and the bottom layer to $1,800 \text{ kg m}^{-3}$, and then (2) varying the depth to the bottom layer (i.e., varying the scale-height of the vertical density-depth profile, the ' H -parameter', hereafter H_{dens}) to match the observed diurnal variations of surface temperatures.

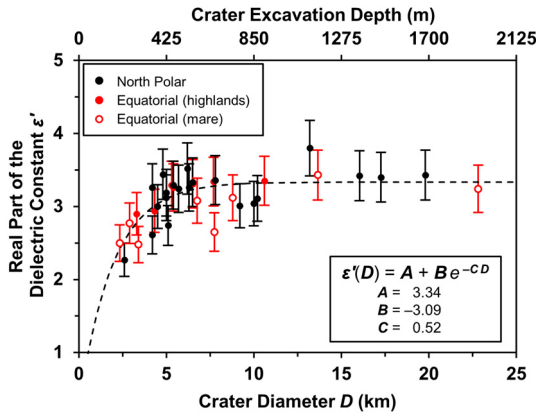


Fig. 7. The surface dielectric constant of lunar regolith fines overlying the crater fills of simple craters as a function of crater diameter, inverted from dual-polarimetric S-band monostatic radar scenes acquired by Mini-RF aboard LRO.

Hayne et al. (2017) find that the density profile scale-height ranges from 2 cm (compact regolith fines) to 9 cm (loose regolith fines). In Fig. 8a, we plot ϵ'_r against the density scale-height H_{dens} of the regolith fines covering the crater fills of equatorial simple craters, but find no clear correlation between the two, suggesting that if a density increase is driving the observed increase of ϵ'_r with crater size, then the denser material lies below the thermal skin depth of the regolith (~ 10 cm) and therefore cannot be sensed or inferred from Diviner's infrared observations.

To explore this possibility, we can estimate bulk density ρ_{bulk} from the observed values of ϵ'_r by assuming that the dielectric properties of lunar regolith fines are primarily dependent on density, and that ϵ'_r follows the power-law dependence on bulk density that was derived from Apollo sample dielectric laboratory measurements (Carrier et al., 1991). However, as previously mentioned, few dielectric measurements of Apollo samples were performed under vacuum conditions or sufficiently desiccated to remove atmospheric moisture contamination (Olhoeft and Strangway, 1975). From this empirical model, we estimate that the bulk density of the uppermost layer of rock-free regolith fines range from $1,280 \text{ kg m}^{-3}$ to $1,830 \text{ kg m}^{-3}$ among the targets of this study—i.e., loose regolith fines on the floors of smaller craters and compact regolith fines on the floors of craters $\gtrsim 5$ -km in diameter. There is no clear physical mechanism that can relate the density or compaction of lunar regolith fines on crater floors to the size of the craters (e.g., Carrier et al., 1991; Hayne et al., 2017). Hence, density variability of regolith fines is unlikely to explain the observed increase in ϵ'_r with crater size.

4.2. Mineralogical variability of regolith fines on crater floors

Next, we consider the hypothesis that the varying dielectric properties of regolith fines covering crater fills can be attributed to different levels of metallic enrichment originating from the different excavation depths of these craters as shown in Fig. 7. For desiccated fines, their dielectric properties are a direct function of their metallic element content (e.g., Heggy et al., 2001; Pettinelli et al., 2005; Heggy et al., 2012). If this assumption is valid, then the increase of the dielectric constant with crater size for diameters < 5 km suggests that the fines excavated from the first ~ 500 m of the subsurface (with a lower dielectric constant) are more depleted than deeper ones (i.e., > 500 m deep) in terms of metal abundance. Hence, the dielectric variation of small craters with diameters < 5 km would suggest an exponential increase in metal abundance with depth in the first 500 m. Moreover, from Fig. 7, we clearly observe that the dielectric constant of these excavated regolith fines is constant for craters with diameters > 5 km, imply-

ing that the metal abundance of the lunar subsurface is constant at depths of ~ 500 m to ~ 2000 m.

To validate this hypothesis, we used surficial FeO abundances derived from SELENE/Kaguya reflectance mapping at 59-m resolution (Lemelin et al., 2016) and surficial TiO_2 abundances derived from LROC WAC band ratios at 200-m resolution (Sato et al., 2017) as they have adequate resolution to explore any potential correlation between crater size and metal abundance of crater-floor regolith fines on their observed dielectric variability. We also compare our results with low-resolution subsurface elemental abundance mapping of Fe (at $0.5^\circ \times 0.5^\circ$ per pixel) and Ti (at $2^\circ \times 2^\circ$ per pixel) by the Lunar Prospector mission that represents metal abundance in the uppermost ~ 1 m of lunar regolith (Prettyman et al., 2006). The above-suggested increase in metal abundance with crater diameter is observed, for example, in highlands craters F5, G4 and E5/Aratus (as labeled in Table 1). Their respective diameters are 5.4, 5.6 and 10.6 km with associated total FeO+ TiO_2 contents of 4.75, 6 and 9.75 wt% (at the surface), and ~ 7.1 , ~ 7.2 and ~ 10.9 wt% (in the uppermost meter of regolith) as shown in Fig. 8b. This observed trend is particularly true of craters in the highlands, but is compromised in mare regions by the terrain's variability in thickness and composition, as we see no clear trend for mare regolith fines in Fig. 8b between FeO+ TiO_2 abundance and crater diameter. Liu et al. (2019) also suggests the occurrence of complex vertical variations in the abundance of FeO and TiO_2 based on microwave sounding data at 3 GHz (S-band) by Chang'E-2 within the first few meters of the lunar regolith. It should also be noted that the FeO and TiO_2 abundances derived from SELENE/Kaguya and LROC WAC reflectance mapping, respectively, relate to compositional changes at the first cm at most, whereas radar-inverted dielectric properties at S-band pertain to the composition of a thicker layer of fines extending from the first several cm to a few tens of cm depth. Although the metal abundances mapped by Lunar Prospector (Prettyman et al., 2006) refer to those in the uppermost meter of regolith, the map resolution is too low (0.5° to 2° per pixel) to resolve craters or their floors. The link between these three sets of compositional observations requires further analysis beyond the scope of this study.

4.3. Potential variability in the ice-enrichment of regolith fines on crater floors

Third, we consider the hypothesis that buried volatiles mixed within the lunar regolith fines could be the driver of the low dielectric constant observed for craters < 5 km in diameter. Laboratory dielectric characterization of lunar analogs in Thompson et al. (2011) suggest that the dielectric constant of loose basaltic fines decrease with increasing ice inclusions at both S and X bands. The trends obtained in these measurements (and not their absolute values) provide a close analogy to the lunar case even though they are not performed at the same temperature and desiccation conditions of the fines filling the craters floors.

Hence, at constant porosity and for a known FeO+ TiO_2 abundance, the low dielectric constant of these fines could be interpreted as the occurrence of minor fractions of subsurface volatiles in polar areas. However, the same increase in ϵ'_r of regolith fines with crater size is observed at equatorial latitudes, suggesting that the curve shown in Fig. 7 represents the dielectric properties of dry, desiccated lunar regolith fines. Hence, we suggest that simple, permanently shadowed crater fills in craters with diameters < 5 km (with $\epsilon' \approx 2.3$ to 3, as shown in Fig. 7) are ideal candidates for the exploration of solid ice presence, since solid ice has $\epsilon' \approx 3$, therefore yielding a measurable dielectric contrast with the surrounding desiccated regolith fines of small crater floors. Alternatively, permanently shadowed craters > 5 km in diameter are nominal candidates for resolving the potential occurrence of

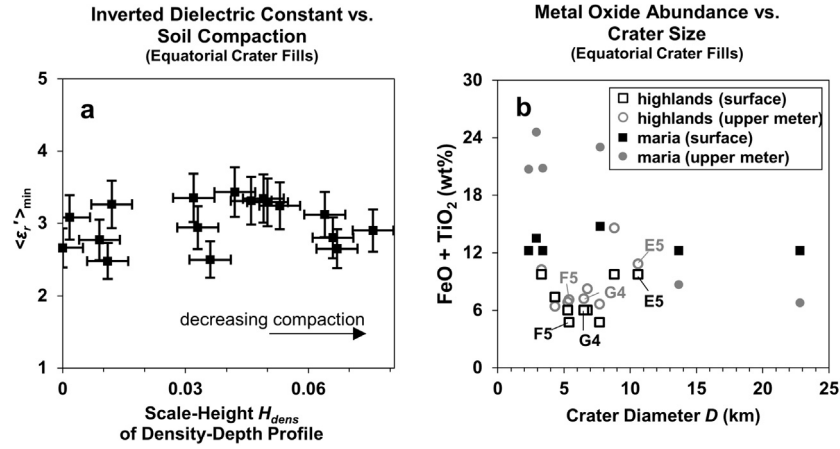


Fig. 8. Comparison of (a) the inverted dielectric constant ϵ'_r of regolith fines selected in this study with their soil compaction (Hayne et al., 2017); and (b) the iron and titanium oxide abundances of these regolith fines at the surface and in the first meter with crater size (Barker et al., 2015; Sato et al., 2017; Prettyman et al., 2006). In plot (a), soil compaction scale height corresponds to the ‘ H -parameter’ or H_{dens} modeled by Hayne et al. (2017) and is related to the distance between the topmost layer of loose regolith fines ($1,100 \text{ kg m}^{-3}$) to the bottom layer of compact regolith fines ($1,800 \text{ kg m}^{-3}$). Soil compaction decreases with increasing scale height for the uppermost $\sim 1 \text{ m}$ of lunar soil. The specific craters labeled in plot (b) show an increase in metal oxide abundance with crater size in the lunar highlands.

porous ice (e.g., Campbell et al., 2006), since porous ice has $\epsilon'_r \lesssim 2$ (Heggy et al., 2019), and dry lunar regolith fines in these larger craters have $\epsilon'_r \approx 3.3$ as shown in Fig. 7, hence yielding sufficient dielectric contrast for radar detection. More S- and X-band radar observations should target the crater fills of these areas to provide further datasets to validate the above hypotheses.

5. Conclusions

Our observations suggest that there is measurable variability in the dielectric properties of regolith fines on lunar crater floors as a function of crater size and potentially as a function of impact excavation depth. In turn, this suggests a vertical gradient in the dielectric constant of the lunar regolith, where it reaches a maximum of $\epsilon'_r \approx 3.3$ for craters $\gtrsim 5 \text{ km}$ in size (corresponding to an excavation depth of $\sim 500 \text{ m}$). Among the hypotheses considered in this study—density variations, metallic enrichment or the potential occurrence of subsurface ice—we find that mineralogical variability is the most supported hypothesis based on observations by SELENE/Kaguya, LROC WAC and Lunar Prospector, providing the most plausible explanation for the observed trend in ϵ'_r with crater size, and together suggest an increase in metal abundance with depth in the original excavated substrate. Finally, we suggest that regolith fines on the crater floors of permanently shadowed craters $< 5 \text{ km}$ in diameter are optimal targets for unambiguous detection of solid water-ice occurrence using S-band radar imaging.

More statistical studies of regolith fines on crater floors are needed in order to validate this result, especially to deconvolve uncertainties in the density and metallic composition effects on the dielectric constant so as to better assess potential ice presence within small polar craters. Future bistatic radar observations of lunar craters acquired by Mini-RF aboard LRO will also contribute to more quantitative assessment of the scattering mechanisms for regolith fines on crater floors at different angles of incidence.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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