Layering Structures in the Porous Material Beneath the Chang'e-3 Landing Site

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Abstract The lunar penetrating radar (LPR) onboard the Chinese Chang'e-3 (CE-3) mission obtained high-resolution profile data for the continuous ejecta deposits of the Ziwei crater. Geological background suggests that the continuous ejecta deposits contain few large boulders, and the ejecta deposits were largely originated from the pre-impact regolith. Using the top ~50 ns of radar data, we estimate the bulk density and porosity for the ejecta deposits based on hyperbolic echo patterns in the radargram that are caused by subsurface boulders. The physical properties are close to those of typical lunar regolith. Numerous subparallel and discontinuous short layers are visible in the radargram of the continuous ejecta deposits. The dielectric coefficients of the layering structures are estimated, and their permittivity is slightly larger than that of typical lunar regolith and less than that of basaltic rocks. Cratering physics together with the geological context of this area suggest that the layering structures are most likely ground gravels and/or melt-welded breccias that were sheared due to the horizontal momentum of the impact ejecta. This interpretation is indicative of the origin of the enigmatic layering structures in regolith core samples returned by the Apollo and Luna missions. The results also highlight the importance of ejecta emplacement in shaping the structure of lunar regolith.

Plain Language Summary Large discrepancies existed in previous geological interpretations using the Chang'e-3 high-frequency LPR data. A comprehensive review of previous studies that used the Chang'e-3 radar data noticed that most previous studies agree that the top ~50 ns of the radargram is restricted within the continuous ejecta deposits of the Ziwei crater. Analyses for the stratigraphy of the landing site suggested that the continuous ejecta deposits were largely composed by pre-impact regolith. Using the high-frequency LPR data, we reconstructed the depth profiles of physical parameters (i.e., relative permittivity, bulk density, and porosity) for the continuous ejecta deposits of the Ziwei crater, which are similar with those of typical lunar regolith. Many subparallel and discontinuous layers are observed in the radargram, which were not deciphered before. We carried out numerical simulations to study the nature of the layering features. Results suggest that these structures have a permittivity slightly larger than that of typical lunar regolith. Geological context of the landing site suggested that the layering structures are likely shear bands within the continuous ejecta deposits, and they may be composed by ground rock fragments and/or melt-welded breccia, which were laterally deformed due to the horizontal momentum of the ejecta deposits.

1. Introduction

Regolith on airless bodies, such as the Moon, is the product of continuous impact cratering and various weathering processes (Hörz et al., 1991). Lunar regolith hosts most of our knowledge of lunar geology and geochemistry acquired by remote sensing, since the wavelengths of most remote sensing techniques are restricted in the upper several meters of the lunar surface (cf. Fa & Wieczorek, 2012).

The conceptual model of lunar regolith consists a uniform layer that has a distinctive boundary with the lower competent rocks (Hörz et al., 1991). However, the detailed structure of lunar regolith is more
complicated than the conceptual model sketched. It has been recognized that regolith thicknesses across the lunar surface are positively associated with surface ages in general (Quaide & Oberbeck, 1968). However, recent evidence suggests that regolith thicknesses across a same geological unit can be different by as much as an order of magnitude (Fa et al., 2014; Wilcox et al., 2005), and this difference is frequently interpreted to be caused by the non-uniform distribution of impact ejecta (Wilcox et al., 2005; Z. Xiao, 2016). Furthermore, displaced and detached boulders should be abundant within lunar regolith (Bandfield et al., 2011), and the boundary between regolith and subsurface competent bedrocks should be diffusive rather than distinct, because fracturing, excavation, and mechanical grinding of rocks are the major mechanism of forming fine regolith (Elder et al., 2019; Wilcox et al., 2005). Due to the vertical heterogeneity of lunar regolith, the consistency of regolith depth measurements using different techniques has been questioned (Fa & Wieczorek, 2012; Hörz et al., 1991; Wilcox et al., 2005; Z. Xiao, 2016).

Lunar regolith usually contains abundant discontinuous layering structures, which were first discovered in the core samples returned by the Apollo and Luna missions (e.g., Fryxell & Heiken, 1974). These discontinuous layers are different from the surrounding regolith in many aspects (D. McKay et al., 1978; Taylor et al., 1979), such as color and texture, mineral assemblage, and grain size distributions. For example, the Luna 24 regolith core tubes contain many layering structures that are distinguished by the interbedding of coarse-grained immature materials and mixtures of fine-grained mature soils (D. McKay et al., 1978). However, the formation mechanism of these layering structures is not understood (D. S. McKay et al., 1991). Unlocking the origin of layering structures is critically important to understand the formation of regolith on airless bodies in general.

The lunar penetrating radar (LPR) onboard the Chang‘e-3 (CE-3) Yutu rover performed the first along-track radar investigation for the subsurface structures of an extraterrestrial body (Su et al., 2014). The LPR consists of two channels that were operated at different frequencies. The first channel was operated at a central frequency of 60 MHz, and the range resolution is ~1 m in lunar basalt-like material (Zhang et al., 2014). The second channel was operated at a central frequency of 500 MHz, and the range resolution is better than 0.3 m in lunar regolith (Fang et al., 2014). While the channel 1 LPR data contain noises that currently cannot be used for reliable geological interpretations (C. Li et al., 2018), the channel 2 LPR data provide an unprecedented opportunity to understand the detailed structure of the lunar shallow subsurface (Dong et al., 2017; Fa et al., 2015; Feng et al., 2017; L. Xiao et al., 2015; J. Zhang et al., 2015; L. Zhang et al., 2019). Beneath the traverse route of the Yutu rover, the continuous ejecta deposits of the Ziwei crater features a high content of fine particles, which cannot be distinguished from typical lunar regolith (section 3.1). Abundant subparallel and discontinuous layers are observed in the CE-3 LPR radargrams, for example, up to five thin layers are recognized in the topmost ~1 m thick regolith (i.e., termed as reworked zone; Fa et al., 2015), but the nature and origin of these layering structures were not revealed. Using the CE-3 channel 2 LPR data, we recognize numerous subparallel, short, and discontinuous layering features in the radargram of the continuous ejecta deposits of the Ziwei crater (section 3.4). The individual layers in the radargram have a much larger thickness than both those discovered in Apollo core tube samples (Fryxell & Heiken, 1974) and those within the shallowest reworked zone (Fa et al., 2015).

This paper is targeted to resolve the nature of these layering structures within the continuous ejecta deposits of Ziwei. We are aware that using the same data set, discrepancies exist in previous interpretations about the subsurface structures of the traverse area due to subjective differences (section 2.3). However, most studies agree that the topmost 50 ns of radar signals was mainly from the continuous ejecta deposits of the Ziwei crater (section 2.3). Therefore, we focus on the topmost 50 ns data set to avoid ambiguous interpretations of the stratigraphy. We first update the depth profiles of various physical properties for the subsurface materials based on an updated radargram. Comparing with similar depth profiles obtained from the Apollo and Luna core samples suggests that the continuous ejecta deposits are more akin to typical lunar regolith than rock rubble (sections 2.3 and 3.2). The updated physical properties of the subsurface materials and forward modeling of radar wave propagation are employed to deduce the possible range of radar permittivity for these layering structures (sections 3.2 and 4.1). The indications of our results to both the cratering process (section 4.1) and the regolith formation process (section 4.2) are discussed.
2. Geological Context, Data, and Method

2.1. Stratigraphy of the Landing Site

The CE-3 landing site is located on a young mare surface (Figure 1) that was formed less than 3.2 Ga (cf. L. Xiao et al., 2015). The geological context of this mare unit has been deciphered in previous studies (e.g., Fa et al., 2015; L. Xiao et al., 2015; J. Zhang et al., 2015), and here we focus on the pre-impact stratigraphy for the Ziwei crater.

The stratigraphic framework of this area can be generally divided into two parts based on the geological context: the bottom layer is the Eratosthenian-aged mare basalts, and the top layer is the ejecta deposits from the young crater Ziwei (Figure 1a). After the formation of the Ziwei crater within the last ~100 million years (e.g., Fa et al., 2015; L. Xiao et al., 2015; J. Zhang et al., 2015), a thin regolith layer has been developed in the top of Ziwei’s continuous ejecta deposits, that is, the reworked zone termed by D. S. McKay et al. (1991) and used by Fa et al. (2015).

From the perspective of impact crater stratigraphy (e.g., French, 1998), we argue that the entire continuous ejecta deposits of Ziwei should be mainly composed of pre-impact regolith. Ziwei is a moderately degraded crater with a rim-to-rim diameter of ~450 m (Figure 1a). The traverse area of the Yutu rover is ~25–50 m from the rim of the Ziwei crater. Referring to the empirical scaling relationship between ballistic distances and ejecta deposit thickness (McGetchin et al., 1973), the theoretical thickness of the continuous ejecta deposits is ~4 m along the traverse area (Fa et al., 2015; Qiao et al., 2016; L. Xiao et al., 2015).
to the empirical relationship that the final crater diameter of simple craters is ~1.3 times that of the transient crater, we can infer that ejecta excavated by the Ziwei crater have a maximum original depth of ~11.5 m based on the relationship between excavation depths and transient crater diameters (Sharpton, 2014). For comparison, the pre-impact target of Ziwei contained a regolith layer and competent basalts. This paleoregolith layer was mainly developed from the Eratosthenian-aged mare basalts. Based on the morphology and reflectance spectra of small impact craters, previous studies suggested that the median thickness of this paleoregolith layer is ~8 m (Fa et al., 2014) and the Eratosthenian-aged mare basalts are constrained as 40–43 m thick (Qiao et al., 2016). It is notable that the thickness of this regolith layer contains a large range of values (Wilcox et al., 2005), but the actual regolith depth at the impact site is a single value. Therefore, the ejecta deposits from Ziwei were mainly from the pre-impact ~8 m thick regolith layer. This is consistent with the fact that although ~4 m long basaltic boulders have been excavated by the Ziwei crater (e.g., L. Xiao et al., 2015), such meter-scale boulders are only visible on top of and within the final crater rim (J. Zhang et al., 2015). Few decameter-scale boulders are visible on the surface along the traverse route of Yutu (Di et al., 2016).

In conclusion, it is plausible that most of Ziwei’s continuous ejecta deposits along the route of Yutu are composed of pre-impact regolith instead of large basaltic boulders, and the continuous ejecta deposits should have similar properties with typical lunar regolith (sections 3.2 and 3.3).

### 2.2. Data

The LPR onboard the Yutu rover was operated from the navigation points N101 to N208 (Figure 1c), ~107.4 m in total (Su et al., 2014; L. Xiao et al., 2015). The channel 2 LPR acquired 2,308 traces of valid data after removing numerous redundant data. The LPR was operated at different modes along the track, which can be divided into five segments (Table 1). From the navigation points N101 to N105, the gain parameters of LPR were adjusted to different values to estimate the best gain value (Table 1). Gains are used to enhance signals reflected by buried boulders without introducing noises to unfavorable levels (Daniels, 2005), and different gain values affect the display depth of radargram. The effects of different gain values on the obtained radar data were discussed in Feng et al. (2017). Zero decibel was chosen to be the best gain value for the channel 2 LPR. Therefore, here we use data obtained from the navigation points N105 to N208 (Figure 2), which corresponds to the traverse distance of ~33.2 to 107.4 m from the landing site (Figure 1c).

During the mission, several reboots of the radar system were carried out due to engineering need, which have caused slightly uneven radargram (Feng et al., 2017) and noises raised by the LPR system and lunar surface environment existing in the raw radargram. To remove these effects, the LPR data are processed following the procedure below: remove redundant data (see supporting information, Figure S1), time zero correction (see Figure S2), equally spaced traces (see Figure S3), remove direct current (DC) component (see Figure S4 and Text S1), background subtraction (see Figure S5 and Text S2), and band-pass filtering (Figure 2a; see also Figure S6 and Text S3) for each trace of valid data (Daniels, 2005).

#### 2.3. Summary of Previous Studies Using the LPR Channel 2 Data

Among previous studies that have used the CE-3 channel 2 LPR data to interpret the local stratigraphy of the landing site, most studies were based on the stratigraphic framework introduced in section 2.1 (e.g., Fa et al., 2015; Feng et al., 2017; Lai et al., 2016; L. Xiao et al., 2015; L. Zhang et al., 2019). Figure 3 shows the comparison of the interpreted subsurface structures using the channel 2 LPR data by previous studies, where vast discrepancies exist. Note that the results are compared using time delay instead of modeled depths, because LPR radar echoes only record the time delay and amplitude, and depths are estimated.
based on the assumed permittivity values (e.g., Figure 2). The major difference among previous studies is the possible locations of the stratigraphic boundaries, which were mainly based on subjective interpretations (Figure 3). For example, whether or not there is a distinct boundary in radar echoes between the continuous ejecta deposits of Ziwei and the underlying paleoregolith is debated. This is due to the fact that the two materials should be both composed of highly fragmented material, and both the thickness of the continuous ejecta deposits of Ziwei and that of the paleoregolith were derived from empirical functions (section 2.1), so that interpretations of possible depth boundaries are somewhat arbitrary (Figure 3).

Based on both the geological context of this region (section 2.1) and the signals revealed in the LPR radargram, most previous studies and also this paper agree that the topmost 50 ns of the radargram is largely restricted in

Figure 2. Radargram of data obtained by the channel 2 LPR onboard the CE-3 mission. The data used in this study are from the navigation points N105–N208. The horizontal axis is the distance along the traverse route (Figure 1c). The right y axis is the two-way travel time of the radar wave. The brightness of the pixel is the strength of the echo, and the relative brightness of materials is independent of the propagation velocity assumed. (a) Fully processed radargram after the procedures introduced in Text S3. Layering structures in the radargram are the alternatively occurring white and black signals, and their differences with hyperbolic echo patterns are introduced in section 3.4. The left y axis is the modeled depth assuming that the radar wave velocity in regolith equals the light speed. (b) Thirty-six hyperbolic echo patterns formed by subsurface boulders are identified within the regolith. Red curves denote the positions of the hyperbolas. The physical properties (i.e., bulk density and porosity) of lunar regolith are estimated based on the hyperboles, and the method is described in section 2.4. The left y axis is the estimated depth that used the average bulk permittivity of regolith (section 3.2). The yellow and blue dashed boxes are the selected end-member cases showing the complexity of the regolith, and these regions are used to analyze the nature of the layering structures within the regolith (sections 3.4 and 4.1). Green arrows and curves represent an uneven echo pattern that is interpreted as the interface between the continuous ejecta deposits of Ziwei and the underlying material. The dashed pink lines show the approximate boundary between the radar-interpreted regolith and subsurface materials. Brown boxes are the two exceptional hyperbolic echo patterns where the estimated average bulk permittivity is significantly larger than that of lunar regolith. (c) Manually sketched layering structures in the upper ~50 ns of the radargram.

Figure 3. Previous interpretations of the subsurface structures at the Chang’e-3 landing site using the LPR high-frequency data set. The vertical axis is time delay, and the horizontal direction is traveling distance.
the continuous ejecta deposits of Ziwei. In our radargram, we notice that at approximately 50 ns, there is a distinct boundary in the echo strength (section 3.1), suggesting that this boundary is most likely a geological boundary where the physical properties of materials dramatically changed (section 3.1). Therefore, we focus on the topmost 50 ns radar data to investigate the detailed structures within the continuous ejecta deposits of Ziwei, which should have similar physical properties with typical lunar regolith (section 2.1).

### 2.4. Physical Properties of Ziwei’s Continuous Ejecta Deposits

The physical properties (i.e., bulk density, porosity, and permittivity) of materials within the upper 50 ns radargram are studied based on hyperbolic-shaped echo patterns that are formed by subsurface boulders. The LPR is essentially a ground penetrating radar (Fang et al., 2014), so boulders in lunar regolith that are equal to or larger than the wavelength of the transmitted radar wave would act as a point scatter. Since both the transmitting and the receiving antennas of a ground penetrating radar have certain beam width (Daniels, 2005), echoes scattered from the subsurface boulders would appear with a hyperbolic shape in the radargram, as the apex of the hyperbola projects to the top of the subsurface boulder (Jol, 2008). Scatters to radar waves are the sources of hyperbolic echo patterns within radargrams, and abundant hyperbolic echo patterns are visible in the LPR channel 2 radargram (Figure 2). The hyperbolic echo patterns were interpreted to be formed by decameter-scale subsurface boulders (Fa et al., 2015; Lai et al., 2016; L. Xiao et al., 2015), which is consistent with the geological context of the CE-3 landing site, since the Ziwei crater was formed within the Eratosthenian-aged basaltic lava plain (L. Xiao et al., 2015).

The geometry of the hyperbolic echo patterns is used to estimate the bulk permittivity of shallower materials. The sizes of the subsurface boulders cannot be reliably derived, because hyperbolic echo patterns are caused by a combination of different factors such as the size, shape, and depth of the subsurface boulder. This method is widely used in ground penetrating radar, and uncertainties in such calculations are ~10%, which are mainly raised from effect of the radius of the buried boulders (Jol, 2008; Shihab & Al-Nuaimy, 2005). The schematic diagram in Figure 4 shows the geometry of radar wave propagation within regolith that hosts a buried boulder. When the LPR is running from the position $x$ and $x_0$, the radar wave will be reflected once hitting a buried boulder that has a depth of $h$. Assuming that the average velocity of radar wave is $v$ and the two-way travel time is $t$, the geometry shown in Figure 4 can be expressed in Equations 1 and 2.

$$z = \frac{vt}{2} = \sqrt{(x-x_0)^2 + h^2} \quad (1)$$

$$t^2 = \frac{(x-x_0)^2}{h^2} = 1 \quad (2)$$

The average propagation speed of radar waves can be derived by fitting the observed hyperbolic echo pattern using Equation 2. The semi-minor axis of the hyperbola is the estimated depth ($h$), and the semi-major axis is two times of $h$ over $v$, that is, $2h/v$. The bulk permittivity ($\varepsilon$) of materials above the scatter can be related to the average propagation velocity using Equation 3, where $c$ is the speed of electromagnetic wave in a vacuum (Ulaby et al., 1981).

$$\varepsilon_{\text{bulk}} = \left(\frac{c}{v}\right)^2 \quad (3)$$

In our calculations for the relative permittivity using hyperbolic echo patterns, the effect of the distance between the LPR antenna and the lunar surface (i.e., $h_{LPR} = 0.3$ m; Xing & Su, 2015) is first evaluated and then ignored to simplify the calculation. $h_{LPR}$ is half the wavelength of the transmitted radar pulse (Fang et al., 2014). Similar procedure has been applied for the CE-3 LPR data in previous studies.
Based on a regolith model that contains stochastically distributed relative permittivity around a given average value (Ding et al., 2017), the effect of $h_{\text{LPR}}$ on the derived relative permittivity based on hyperbolic echo patterns is constrained to be ~13% (see Figure S8), which is comparable with the inherent uncertainty associated with the general method (Shihab & Al-Nuaimy, 2005).

Studies of Apollo core samples demonstrated that the bulk permittivity of lunar regolith ($\varepsilon_{\text{bulk}}$) is related with the bulk density ($\rho_{\text{bulk}}$), and Equation 4 shows the empirical relationship (Carrier et al., 1991).

$$\varepsilon_{\text{bulk}} = 1.919 \rho_{\text{bulk}}$$ (4)

The bulk density is directly associated with porosity ($n$) if the grain density ($\rho_{\text{grain}}$) is known (Houston et al., 1974), and Equation 5 shows the relationship between grain density ($\rho_{\text{grain}}$) and porosity ($n$) of lunar regolith (Carrier et al., 1991). Typical grain density of lunar regolith is usually assumed to be 3.1 g/cm$^3$ (J. Mitchell et al., 1972).

$$n = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{grain}}}$$ (5)

The relationship between the bulk density and depth ($d$) of regolith is described as $\rho_{\text{bulk}} = a \times (d + b)/(d + c)$, where $a$, $b$, and $c$ are unknown variables that can be estimated using least square method. Equation 6 shows the bulk density profile revealed by the Apollo 15, 16, and 17 core samples (Carrier et al., 1991).

$$\rho_{\text{bulk}} = 1.92 \frac{d + 12.2}{d + 18}$$ (6)

### 2.5. Numerical Simulation of the LPR

Numerical simulation for the propagation of radar waves is employed here to both verify the existence and deduce the permittivity of the layering structures within the continuous ejecta deposits. We set up different lunar subsurface models to simulate the propagation of LPR radar waves. The dielectric permittivity is a complex quantity that consists of a real and an imaginary part. The real part affects the propagation speed of radar waves in the material, and here the estimated bulk permittivity (section 3.2) was assumed to be real part of the dielectric permittivity in our models. The imaginary part of the dielectric permittivity is related to the electromagnetic energy loss within regolith, and this parameter is mainly affected by the contents of TiO$_2$ and FeO (Olhoeft & Strangway, 1975). The content of TiO$_2$ + FeO of the surface material at the CE-3 landing site was calculated to be ~25.5% based on measurements made by the visible and near-infrared imaging spectrometer spectra aboard the Yutu rover (J. Zhang et al., 2015). Therefore, the loss tangent (the ratio between imaginary and real part of complex permittivity) used in our lunar regolith models is 0.0247 using the empirical equation derived from Apollo samples (Carrier et al., 1991).

$$\tan \delta = 10^{0.045(\text{TiO}_2 + \text{FeO})/70 - 2.754}$$ (7)

The two-dimensional finite-difference time-domain code (FDTD-2D; Irving & Knight, 2006) is employed to simulate the propagation of radar waves in the modeled material. FDTD performs differential iteration calculation of Maxwell’s equations of electromagnetic waves, and it is widely used to simulate electromagnetic wave propagation (Teixeira et al., 1998; Yee, 1966). Three-dimensional (3D) simulations of FDTD can be used to fully resolve the propagation of radar waves in full space. However, it is computationally expensive for a large number of simulations like we have carried out here (sections 3.4 and 4.1; see also Table S3). Two-dimensional simulations are less expensive in terms of computation resources, and it is more feasible to analyze large regions than 3D models. More importantly, 2D and 3D models are both based on the physical basis of radar wave propagation, and when they are used together for the same model, the shapes of waveforms (including the peak arrival times) are consistent with each other (Belli et al., 2009; Zhan et al., 2009). Therefore, the FDTD-2D code is used for our purpose.

Similar modeling work has been carried out to analyze the thickness and interior structures of lunar regolith at the CE-3 landing site, and possible dielectric permittivity of the subsurface materials was derived using
inverse calculation (Ding et al., 2017; Lai et al., 2017; J. Li et al., 2017). However, the comparison between the modeled regolith structure and the observed LPR radargrams was not done at the same dimension in previous studies (Lai et al., 2017). In some cases, interpretations were merely based on the LPR synthetic data (J. Li et al., 2017). Here, our modeling works remedy such defects since the simulated radargrams are compared with the LPR channel 2 data with the same dimension, that is, both the same survey distance and the two-way travel time.

3. Results

3.1. Boundary of Loose Materials at the CE-3 Landing Site

A sharp but laterally discontinuous echo pattern is visible at ~50 ns of the radargram (i.e., green lines in Figure 2b). This interface is caused by an abrupt increase in the amplitude of the reflected echoes (Figure 5), which may correspond to a sharp increase in the permittivity. We concur with previous studies that this boundary might be caused by an increased bulk density (Fa et al., 2015; Qiao et al., 2016; L. Xiao et al., 2015). Regarding the geological context, materials beneath this echo pattern may be either highly compacted paleoregolith due to the overburden pressure (e.g., Fa et al., 2015; L. Xiao et al., 2015) or broken basalts (e.g., L. Zhang et al., 2019) that are detached from the competent bedrock.

The depth of this echo pattern is ~4.2 m referring to the estimated average bulk permittivity of $\varepsilon_{\text{bulk}} = 3.23 \pm 0.61$ (section 3.2). This boundary is uneven along the traverse route of Yutu, for example, ~3.7 m at N105, ~4.2 m at N106, ~3.4 m at N107, and ~4.3 m at N202–N206. The dashed purple lines denote the interpreted layer where the echo patterns are not so obvious, and they are determined following the trend of the green boundary in the radagrams shown in Figure 2b.

Figure 5. Nine traces of A-scan of the high-frequency LPR radargram (Figure S7 shows the positions). Red arrows point to the abrupt increases in the amplitude of the reflected echoes, which are interrelated as the interface between the continuous ejecta deposits of Ziwei and underlying more competent materials.

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3.2. Bulk Permittivity of the Continuous Ejecta Deposits

The number, location, and shape of possible hyperbolas identified in the radargram are critical to the calculation of the bulk permittivity for the regolith. Criteria used in selecting suitable hyperbolic features are twofold: the hyperbolas appear as distinct arc curves that have completed hyperbolic apexes, and the hyperbolas have partially or completely developed two wings. Identifying hyperbolas is a manual process, and previous studies have reported different numbers of hyperbolas in the LPR channel 2 data, for example, 50 in Fa et al. (2015), 20 in Lai et al. (2016), and 48 in Feng et al. (2017). In this study, 36 hyperbolic echo patterns are recognized in the radargram (Figure 2b). Table S1 shows the detailed information for each echo pattern. Figure 6 shows the shape of hyperbolic echo patterns observed within the radargram. We must note that the actual number of hyperbolic echo patterns might be larger than 36, and here we only selected the most likely ones. Most of them are located between ~10–60 ns and few exist at depths less than ~10 ns. The possible effect of the number of hyperbolic echo patterns on the estimated bulk permittivity is not determined yet, but the 36 recognized hyperbolas occur within the entire 50 ns of the radargram (Figure 2b), so that the estimate bulk permittivity could represent the depth range of radargram studied.

The hyperbolic echo patterns are manually extracted using closely spaced points along the echo patterns, and Equation 2 is used to fit the hyperbolic shape. The estimated root mean square (RMS) bulk permittivity of the regolith has 95% confidence interval, and this value ranges between 2.15 ± 0.15 and 4.26 ± 0.13, with an average value of 3.23 ± 0.61 (Figure 7). For comparison, we have compiled the measured permittivity values of Apollo regolith samples, which are from ~1.65 to 4.43. The statistic histogram of our estimated RMS bulk permittivity and the permittivity values measured from Apollo samples is shown in Figure 7. The bulk permittivity of the subsurface materials along the traverse route of Yutu is within the range for Apollo regolith samples and towards the larger values (see Table A9.16 of Carrier et al., 1991). This is due to the greater penetration depth of the LPR compared with Apollo regolith cores.

On the other hand, two of the 36 hyperbolic echo patterns yield RMS bulk permittivity larger than 10, for example, the two hyperbolic echo patterns marked in the brown boxes of Figure 2b. The larger RMS bulk permittivity is likely due to a local concentration of <30 cm basaltic boulders in the ejecta deposits, which do not form hypervbolic echo patterns at smaller depths but still cause the larger bulk permittivity. Only

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**Figure 6.** Hyperbolic echo patterns observed within the radargram obtained by the CE-3 channel 2 LPR. Numbers started with p denote the number of the echo patterns. Blue dots are the extracted points along the echo patterns, and the red lines are the fitted hyperbola functions.
few such hyperbolic echo patterns are recognized, and this observation is consistent with the rockless appearance along the traverse zone (Di et al., 2016). In conclusion, the bulk permittivity of the continuous ejecta deposit of Ziwei is consistent with that of typical lunar regolith.

3.3. Bulk Density and Porosity of the Continuous Ejecta Deposits

The bulk density and porosity of the continuous ejecta deposit of Ziwei are estimated based on the estimated bulk permittivity using the methods introduced in section 2.4. Figures 8a and 8b show the results. It is notable that the bulk densities are for materials at depths less than those of the hyperbolic echo patterns (Jol, 2008). Equation 8 shows the fitted depth profile of the derived RMS bulk density.

\[ \rho_{\text{bulk,LPR}} = 2.52 \frac{d + 10.48}{d + 59.13} \]  

(8)

To further constrain the possible bulk density and porosity distributions (Figures 8a and 8b) at different depths, the interval values of radar wave velocity \( (v_n) \) is calculated, so that the physical properties of Ziwei’s continuous ejecta deposits and that of typical lunar regolith can be better deciphered. The interval velocity \( (v_n) \) is estimated from the RMS velocity \( (v_n) \) and time delay \( (t_n) \) at the at nth layer using the Dix equation (Equation 9; Dix, 1955).

\[ \tilde{v}_n^2 = \frac{t_n v_n^2 - t_{n-1} v_{n-1}^2}{t_n - t_{n-1}} \]  

(9)

Using this method, the estimated interval density of Ziwei’s continuous ejecta deposits is \( \sim 1.61 \text{–} 2.45 \text{ g/cm}^3 \). Considering errors (see Text S4, Figure S10, and Table S2 for the calculation procedure of errors), the density values are within the range of measured density for Apollo samples. For example, the bulk densities of the lunar regolith recovered from Apollo 11, 12, and 17 core tubes are 1.36–1.80, 1.6–2.0, and 1.57–2.29 g/cm³, respectively (Costes et al., 1970; J. K. Mitchell et al., 1973; Scott et al., 1971). In the first meter, the depth profile of the derived interval bulk density is different from the depth-density profile estimated using the Diviner data (Figure 8c; Hayne et al., 2017). The \( H \) value at the landing site is \( \sim 0.062 \) (Figure S9), and the corresponding regolith density profile within 1 m is compared with the depth profile of interval densities derived from the LPR data (Figure 8c). The two profiles show different patterns, because the density profile estimated (red line of Figure 8c) based on the thermophysical properties follow an exponential function (equation 1 shown in Hayne et al., 2017) but the interval densities (blue line of Figure 8c) derived from the hyperbolic echo patterns.
patterns of the high-frequency LPR radargram. On the other hand, the derived interval values of bulk densities yield a porosity of ~44.69% for the top ~0.3 m materials of Ziwei's continuous ejecta deposits. This is consistent with that of the top 0.3 m regolith within the Apollo 15–17 core samples (49 ± 2%; J. Mitchell et al., 1974). Analyses of astronaut bootprints yielded an average porosity of ~46.7 ± 4% for the surface regolith (Houston et al., 1974; J. Mitchell et al., 1974; Mitchell et al., 1973). Such comparisons confirm the plausibility of this method.

The comparisons above suggest that the physical properties of materials within the topmost ~50 ns of the radargram (i.e., continuous ejecta deposits of Ziwei) are comparable with those of typical lunar regolith. This is consistent with our estimate based on the general geological context (section 2.1).

### 3.4. Layering Structures Within the Continuous Ejecta Deposits

Abundant subparallel and discontinuous layers are visible in the top 50 ns of the radargram (Figure 2c). These features appear substantially thicker than those observed in the near-surface rework zone (Fa et al., 2015). Liu et al. (2013) found that abundant subsurface boulders can cause similar layering structures in radargrams. However, the surface along the entire traverse route of Yutu is generally free of rocks >0.3 m in diameter (Di et al., 2016), and abundant subsurface boulders would cause much larger permittivity than we have estimated in section 3.2 (Figure 7). Using numerical simulations, we have investigated whether or not buried boulders could cause similar layering structures in loose materials like the observation shown in Figure 2c. Scattered echoes induced by subsurface rock breccia appear as either hyperbolic echo patterns or strongly curved patterns in the radargram, unlike the observed subparallel and discontinuous layers (see Text S5 and Figure S11).
Numerical simulation and cross comparison are used together to investigate the nature of these layering structures. To testify the reliability of this method, we have chosen two test areas, where few hyperbolic echo patterns are visible (regions A and C shown in Figure 2b), to deduce the possible ranges of relative permittivity of the layers. In principle, the selection of test areas can be arbitrary in the entire radargram (Figure 2a), because numerical models can accommodate different complexities in the observed subsurface structures. Regions A and C shown in Figure 2b contain few hyperbolic echo patterns, so that possible scattered signals can be minimized for the model construction and result comparison. The radargrams of the two areas are updated using the depth profile of permittivity shown in Figure 7b. The layering structures are

Figure 9. Numerical simulation of radar wave propagation in the continuous ejecta deposits of Ziwei and comparison of the modeled radargram and the LPR observations. The two test areas in Figure 2b are selected, where few boulders are visible. Both the modeled regions have identical horizontal distances of 5 m and depths of 6 m. (a) The LPR radargram for test area A in Figure 2b, and the lines with different colors represent the locations of the layering structures. (b) The regolith model for test area A. The bulk permittivity profile is adapted from Figure 7b. Color bar shows the value of the assumed permittivity. The layers are assumed to have a permittivity of 5. Panels (c) and (d) are the radar observations and regolith model for test area C shown in Figure 2b. The model setup is identical with that of region A. Panels (e) and (g) are the radargrams of test areas A and C, respectively. Panels (f) and (h) are the simulated radargrams for test areas A and C, respectively.
manually extracted (e.g., Figures 9a and 9c), and the actual geometry of both the test areas and the layering structures is used as the input in our FDTD models. As a preliminary model test, the permittivity of the layering structures is assigned as 5, considering that the permittivity might be somewhat lower than that of competent rocks (Kiefer et al., 2012) and larger than that of typical regolith (Figure 7). Detailed constraints on the other possible relative permittivity are deciphered in section 4.1. The conductivity distribution of the models (Figure S12) is derived from the loss tangent using Equation 10 (Ulaby et al., 1981).

\[
\sigma = \frac{2\pi f \varepsilon_0 \varepsilon_{\text{bulk}} \tan \delta}{\delta}
\]  

where \( f \) is the center frequency of the channel 2 LPR (500 MHz); \( \varepsilon_0 \) is the vacuum permittivity of approximately \( 8.85 \times 10^{-12} \) \( F/m \); and loss tangent (\( \tan \delta \)) is assumed to be 0.0247 as described in section 2.5. The space interval in our model is \( 0.01 \times 0.01 \) m, and the time window is set to be 100 ns. Five hundred megahertz is used as the modeled frequency bandwidth of the transmitted radar signal in our models, which is identical with that of the channel 2 LPR, and the input waveform in our model is updated from Fang et al. (2014). The modeled radargrams and LPR observations are compared in both the same time window (100 ns) and horizontal scale (5 m).

The model setups for the two test areas are illustrated in Figures 9b and 9d, and the simulated results are shown in Figures 9f and 9h. The results and observations are similar in appearance. We use the Bhattacharyya coefficients to quantitatively evaluate the similarity between the observed and modeled radargrams. The Bhattacharyya coefficient describes the similarity between gray-value histograms of two images (Khalid et al., 2005), with 1 representing a perfect match and 0 representing a complete unmatch (Bhattacharyya, 1943). The Bhattacharyya coefficient is 0.847 for Figures 9e and 9f and 0.836 for Figures 9g and 9h, so that the regolith models are representative for the two test areas, and the layering structures might correspond to materials that have a relative permittivity between that of typical lunar regolith and basaltic boulders.

4. Discussions

4.1. Nature and Origin of the Layering Structures

The nature of the layering structures within the continuous ejecta deposits can be deduced based on the estimated relative permittivity. To quantify the possible range of relative permittivity for the layering structures, we built different regolith models that have implanted thin layers with a large range of permittivity values. To further approach the complexity of the observed radargram, region B outlined in Figure 2b is used as the study area for this purpose, as a hyperbolic echo pattern is visible in this area. The simulated results are tested against the observation, and the similarity is evaluated based on both the modeled and observed radargram and whether or not the hyperbolic echo pattern is visible in the modeled radargram. The regolith models are constructed using the method introduced in sections 2.4 and 3.4. The background depth profile of relative permittivity for the continuous ejecta deposits is adapted according to Figure 7b, and the relative permittivity of the layering structures is assigned with different values (1.5 to 7.5) to check the possible range. The size and shape of this boulder are not constrained (section 3.4). For the models shown in Figure 10, a cycloidal-shaped boulder with a diameter of 0.3 m is planted at a depth of \( \approx 2.75 \) m. This boulder is regarded as a lunar basalt rock and the bulk permittivity is assumed to be 5 to 9 with an interval of 1. The other models and results, which consider relative permittivity as 6–8 for the buried boulders, are presented in Figures S13–S15. Furthermore, both the shape and the size of the subsurface boulder are varied in our models, and the results suggest that the shape and size of the buried boulder do not affect the final result (see Texts S7–S8 and Figures S17–S18). The detailed model parameters set in this study were summarized in Table S3.

When the relative permittivity of the layering structures is less than that of the buried boulder, the modeled radargram is similar with observed radargram (Figure 10; see also Figures S13–S15 and Text S6). To quantify the similarity, we compare the amplitude of each peak echo pattern (dB) in the topmost \( \approx 40 \) ns of the simulated (red line) and observed (green line) radargrams, that is, above the buried boulder. Note that the absolute amplitudes of the modeled and observed echo patterns cannot be directly compared, because the estimated RMS bulk permittivity profile (Figure 7b) does not strictly equal that of the actual value. For comparison, the peak amplitudes of each A-scan are normalized to the number of received peaks. The
Figure 10. FDTD simulation of radar wave propagation in the continuous ejecta deposits of Ziwei. The test area is for region B shown in Figure 2b, which is ~5 × 7 m in dimension. The buried boulder is placed at a depth of ~2.75 m according to the observation, and the diameter is set to 0.3 m here. The depth profile for the bulk permittivity of the continuous ejecta deposits is adapted from that shown in Figure 7b. The relative permittivity of the layering structures is set to different values (1.5–7.5) in the models. Note that the effects of the shape and size of the buried boulder on the results have been systematically tested (see Figures S14 and S15 for detailed information). The two radargrams in the first column are the same LPR radargrams observed for region B in Figure 2b. The rest of the top rows shows the model setups considering a relative permittivity of 5 for the buried boulder, and the second row shows the corresponding simulation results. The third row shows the model setups considering a relative permittivity of 9 for the boulder, and the fourth row presents the model results.
Statistic results are shown in Figures 11 and S16. For example, for models that assumed a relative permittivity of 5 for the implanted boulder (first row of Figure 10), the amplitude distributions of the simulated and observed echo patterns are consistent with each other when the permittivity of the layering structures is ~4.5. For the models that assumed a relative permittivity of 9 for the implanted boulder (third row of Figure 10), the simulation and observation are consistent with each other when the permittivity of the layering structures is between ~4.5 to 5.5 (Figures 10e_m, 10f_m, 10m_m, and 10n_m). Therefore, comparing the simulated radargrams with observations suggests that the permittivity of the layering structures is between that of the regolith and basaltic boulders. It is a semi-quantitative estimation that the relative permittivity of the layering structures is between ~4.5 to 5.5, because the actual relative permittivity could be derived only if the exact properties of both the background materials and the implanted boulders are known.

The estimated relative permittivity for the layering structures can be caused by a combination of different physical and/or chemical properties of materials that have enlarged the bulk density and/or decrease the porosity compared with normal regolith (Carrier et al., 1991). However, the nature of the layering structures cannot be conclusively solved without in situ core samples. Core samples of lunar regolith have been retrieved from the six Apollo landing sites (D. S. McKay et al., 1991), and layering structures have been observed in all the core samples (Duke & Nagle, 1976; G. Heiken et al., 1976; Taylor et al., 1979). For example, 42 distinct textural units that are poorly sorted were found in the 236 cm deep core drilled by Apollo 15 (G. H. Heiken et al., 1974; G. Heiken et al., 1976), and 46 textural units were found in the 221 cm long core recovered from Apollo 16 (Duke & Nagle, 1976). However, both the physical and the chemical properties of the lunar regolith vary in a complex and non-systematic way, and they are not tightly related to the layering structures observed in the core samples (Carrier et al., 1991). More importantly, the consistency between the layers in the regolith core samples and the layering features in the radargrams has not been resolved. Therefore, the nature of the observed layering structures in the radargram cannot be answered by comparing with the Apollo core samples.

The layering structures are formed during the emplacement of the continuous ejecta deposits of Ziwei, and the source of the continuous ejecta deposits is largely from the pre-impact regolith with a minor contribution from basaltic fragments (section 2.1). Assuming that materials within the layering structures have similar
compositions with the surrounding regolith, the slightly enlarged bulk permittivity suggests that the layering structures might be impact melt-welded regolith breccia, and their bulk density is slightly larger than that of typical regolith (D. S. McKay et al., 1991; Figure 7a). During the cratering process that formed the Ziwei crater, both melt and unmelted materials were launched together (Osinski & Spray, 2001). Before leaving the excavation cavity, the impact melt has moved along the walls of the excavation cavity, mixing with the regolith along the path (Melosh, 1989). Although impact melt formed by small craters is generally with both small volume and rapid cooling rate, impact melt is superheated (Denevi et al., 2012), and they have been widely observed on the rim and continuous ejecta deposits of small impact craters (Stopar et al., 2014). Therefore, when the mixture of impact melt and solid regolith was landed, the horizontal momentum may have caused internal shearing of the breccia, forming the short and discontinued layering structures. This is supported by the observed cascading ejecta flows around small and fresh impact craters (Bandfield et al., 2014). On the other hand, if assuming that materials within the layering structures have similar composition with the basaltic rocks, their smaller permittivity would indicate a less bulk density and larger porosity. This assumption would suggest that layers are composed by ground basaltic rocks that were fragmented during the emplacement of the continuous ejecta deposits. The small basaltic fragments have much smaller sizes than the wavelength of the radar waves, so that no hyperbolic echo patterns are formed in the radargram.

4.2. Indications to Regolith Formation

Horizontal shearing of melt-welded regolith breccia and/or ground rock fragments should be a common product during the formation of small impact craters on the Moon and other airless bodies. We propose that these products should commonly exist within lunar regolith throughout the lunar history, and they might also explain some of the observed layering structures within the Apollo and Luna core samples (D. S. McKay et al., 1991) and the similar layering structures in the reworked zone of the LPR radargram (Fa et al., 2015).

It is widely believed that lunar regolith is composed of discrete layers of material ejected from various-sized impact craters. However, detailed studies of the Apollo core samples have not been able to assign individual layers as possible ejecta from a known impact crater (D. S. McKay et al., 1991). The Apollo 12 astronauts sank two 42 cm long drive tube cores on the rim of a 10-m diameter crater, and 10 discrete layers were found within the core (Fryxell & Heiken, 1974). These layers are part of the continuous ejecta deposits of the small crater, and the layers are mainly recognized on the basis of sharp changes in grain sizes and grading between adjacent layers. The geological context of this core sample is identical with that of CE-3 LPR investigation area, suggesting that at least grinded rock fragments could be the reason for the forming of the layering structures in the radargram. Likewise, up to two to five sublayers are recognized in the CE-3 channel 2 LPR radargram at the topmost 1 m (Fa et al., 2015). The traverse route of the Yutu rover has crossed a lot continuous or discontinuous ejecta deposits of various-sized small craters in this area (Figures 1b and 1c). It is likely that these sublayers are formed by similar processes due to internal shearing when ejecta deposits were emplaced.

5. Conclusions

We revisited the high-resolution radar data obtained by the channel 2 lunar penetration radar onboard the CE-3 mission. Most previous studies on the local stratigraphy recorded in the radar data agreed that the shallow subsurface is dominated by the continuous ejecta deposits of the Ziwei crater. We have further analyzed the relative permittivity, bulk density, and porosity for the continuous ejecta deposits, approving that these materials are not distinguishable from typical lunar regolith. This result is supported by the pre-impact stratigraphy of the Ziwei crater.

Changing the perspective on the nature of the continuous ejecta deposits, we investigated the nature of the abundant discontinuous and short layering structures in the radargram. Our numerical modeling and cross comparison suggest that the layering structures are composed of materials that have slightly larger permittivity than typical lunar regolith. Combining the geological context of the layering structures, we speculate that the layering features are caused by either melt-welded regolith breccia and/or grinded rock fragments that have limited lateral distribution. This interpretation is consistent with the physics of cratering process, since impact ejecta are deposited with horizontal momentum, so that mixing and shearing should be
common within the ejecta. This explanation is also feasible to interpret the origin of similar features found in Apollo and Luna core samples and other radagrams, which have been enigmatic for over half of century.

The discovery in this paper may be verified very soon by the coming Chang'e-5 mission, which will be launched at late this year. This mission is targeted to return core samples from the lunar mare, together with a lunar penetration radar system (Y. Xiao et al., 2019). With the Chang'e-5 samples and radar data, we believe that the interpretation in this paper can be tested, and the long mystery of lunar regolith structure could be solved with a conclusive answer. The results will be broadly interesting for all airless bodies.

Data Availability Statement

LPR data can be downloaded at http://moon.bao.ac.cn.

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