Revisiting the Subsurface Stratigraphy of the Jezero Crater Floor using the RIMFAX GPR.

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Introduction: An understanding of the relative timing of the emplacement of various units across the Jezero crater floor is important. Subsurface stratigraphy of Jezero is complex with the interplay of sedimentary and magmatic processes, later erosion, transport of eroded surface materials through aeolian processes, and later impact cratering. Impact craters punched through the crater floor materials. The walls of the craters provide a possible glimpse of internal layers within the Jezero crater floor. The ejecta of older craters could also be interspersed with previously identified crater floor units. Here we examine the subsurface stratigraphy imaged by RIMFAX on sols 383-398 where *Perseverance* continued northwest past OEB on the Máaz formation toward the delta (Fig. 1A).

The Radar Imager for Mars' Subsurface Experiment (RIMAX) ground-penetrating radar (GPR) on the Mars 2020 *Perseverance* rover is a frequency modulated continuous wave (FMCW) system operating at 150-1200 MHz [1]. RIMFAX has successfully collected images of the subsurface since landing at the Octavia E. Butler (OEB) site on 18 February 2021 (Sol 0). *Perseverance* initially skirted and then entered the igneous Séítah formation on the crater floor and then returned to OEB along its original route [2,3,4]. RIMFAX detected abundant, dipping subsurface layers along these traverses collected from Sol 15 up to Sol 280 [4]. RIMFAX continued to image subsurface stratigraphy across the remainder of the crater floor as *Perseverance* approached the delta deposits.

Setting of Sols 383-398: Sols 383-398 comprise a section of traverse where *Perseverance* turned northwest toward the Jezero Delta to skirt the Séítah formation. The rover passed between a collection of impact craters of various diameters along this section. The craters are in varying states of degradation. Two larger, named craters close to the traverse are La Orotava (D ~ 320 m) and Port Angeles (D ~ 175 m). Several other, smaller craters are scattered on either side of the traverse. One crater (D ~ 33 m) appears fairly fresh with dark rays of ejecta visible on the surface (Fig. 1A). Blocks from this ejecta blanket are visible in images collected by the *Perseverance* Navigation Cameras (Navcams).

Methods: Radar data are collected laterally as a series of soundings as the rover traverses the crater floor. The two-way travel time is recorded between the transmitted wave and the reflected wave received from any subsurface structure. As RIMFAX samples the subsurface, a 2D image of the 3D volume of subsurface, or radargram, is generated. Bright reflections in the radargrams are generated where a contrast in density is present in the subsurface.

Radar Wave Velocity and Permittivity. Depth to a particular feature and its vertical extent is inferred by measuring the radar wave velocity as it propagates through the media. The relationship between radar velocity and relative dielectric permittivity ($\boldsymbol{\varepsilon}_r'$) is $v = c/\sqrt{\boldsymbol{\varepsilon}_r'}$ for dry, non-magnetic materials. Radar wave velocity can be estimated by fitting a theoretical hyperbola to a hyperbolic form in the radar image generated by the motion of RIMFAX as it passes toward, over, and away from an embedded refractor (point source) [5]. We use the methods of [5] to estimate the radar wave velocity and assign this spatially uniform, depth-independent velocity to the radar data to convert the round-trip travel times to depth. These depths are later adjusted for topography.

Permittivity is also related to the bulk density through empirically-derived equations of the general form $\boldsymbol{\varepsilon}_r' \sim 2^{\rho}$ [6]. We estimate the permittivity from the radar wave velocity followed by the bulk density.

Preliminary Results: Hyperbola matching resulted in a mean bulk radar wave velocity of 0.11 m/ns. Successful hyperbola fits were taken at the surface to depths up to 5 m. This velocity was applied to all the radargrams from Sols 383-398 uniformly to estimate depth to particular features. This velocity translates to $\boldsymbol{\varepsilon}_r' = 7.4$. This yielded a bulk density of ~2.9 g cm^{-3}. This density is lower than estimates for earlier Sols [5].

Radar data collected on Sols 384-386 show packages of NE dipping reflectors as steep as ~15º are observed as in [4] as *Perseverance* traveled northwest and parallel to the Séítah formation (Fig. 1A). These layers are observed at depths as shallow as ~5 m up to ~12 m. On Sol 384, one such dipping reflector may extend to the surface at ~60 m and ~160 m along that section of traverse. Layers dip away from Séítah on Sols 383-386.

From Sol 386 to 389, a sequence of nearly horizontal, laterally continuous layers are observed. These layers generate strong, bright reflections in the radargrams as *Perseverance* approaches a more heavily cratered region of the crater floor between the end of the traverse on Sol 386 to Sol 389. These reflectors are separated by a reflection-free "low reflectivity zone" (see [4]). In some cases, layers are continuous for many tens to hundreds of meters (see Fig. 1C). These layers are seen at depths as shallow as 3 m down to depths of 8-10 m. Figs. 1B and 1C are an example of a series of three bright, nearly horizontal reflections separated by regions of lower reflectivity collected on Sol 389. Shallow layers at depths of ~3 m are separated from the surface by a low reflectivity zone. Earlier Sols show shallow (≤ 3 m), undulating layers on scales of Some of these layers take on a concave shape, particularly at the end of the Sol 386 traverse, where they extend toward the surface.

Conclusions and Future Work: It is likely that the layers dipping up to 15° are a continuation of igneous or sedimentary layering dipping away from Séítah as concluded by [4]. Further investigation is necessary to determine if these layers correspond to any outcrops on the surface.

The deeper, nearly horizontal, laterally continuous layers could be contacts between the Máaz and Séítah formations. The shallower, ≤ 3 m depth layers could be associated with layers of ejecta from the smaller craters that the rover passed on Sols 386-389. These layers could alternatively be a layer of regolith or materials transported by aeolian means. Permittivity measurements cannot resolve this ambiguity presently without additional observations.

The estimated $\boldsymbol{\varepsilon}_r'$ of 7.4 and corresponding density measured from hyperbolas at relatively shallow depths is within the range for a Martian basalt as measured by [5]. However, it is somewhat lower than their mean of 9. Permittivity estimated using a hyperbola fitting method is a bulk property of the subsurface above the embedded scatterers used in the fitting. It is therefore subject to the cumulative properties of the mixture of materials that could be present.

There are a variety of possible interpretations for the observed layering and permittivity measurements. Most simply, the hyperbola-derived permittivity indicates that the shallowest layer (reaching depths up to 5 m) is a unit of mostly coherent rock. The lower measured permittivity (compared to [5]) indicates this layer could be a somewhat more porous rock with a lower density than many other basalts, or it could possess regions of unconsolidated blocks, or the layer could be consolidated crater ejecta and/or regolith. The low-reflectivity regions result from low internal scattering on length scales < 10 cm (see [4])and a lack dielectric contrast. This indicates either a homogeneous region of subsurface or relatively fine-grained material at scales less than the minimum free-space radar wavelength (25 cm). The permittivity measurements are also consistent with lower density sedimentary materials.

Further investigation of available imagery will be necessary to confirm the origins of these shallow, undulating layers at ≤ 3 m. More hyperbola fits will be performed to establish whether a transition in $\boldsymbol{\varepsilon}_r'$ occurs along this section of traverse. This will also help to determine if the upper subsurface is homogeneous as concluded by [5]. Further insight could also be gained by examining the radar signal attenuation, which is partially related to composition and other physical properties of the materials in the subsurface [7].

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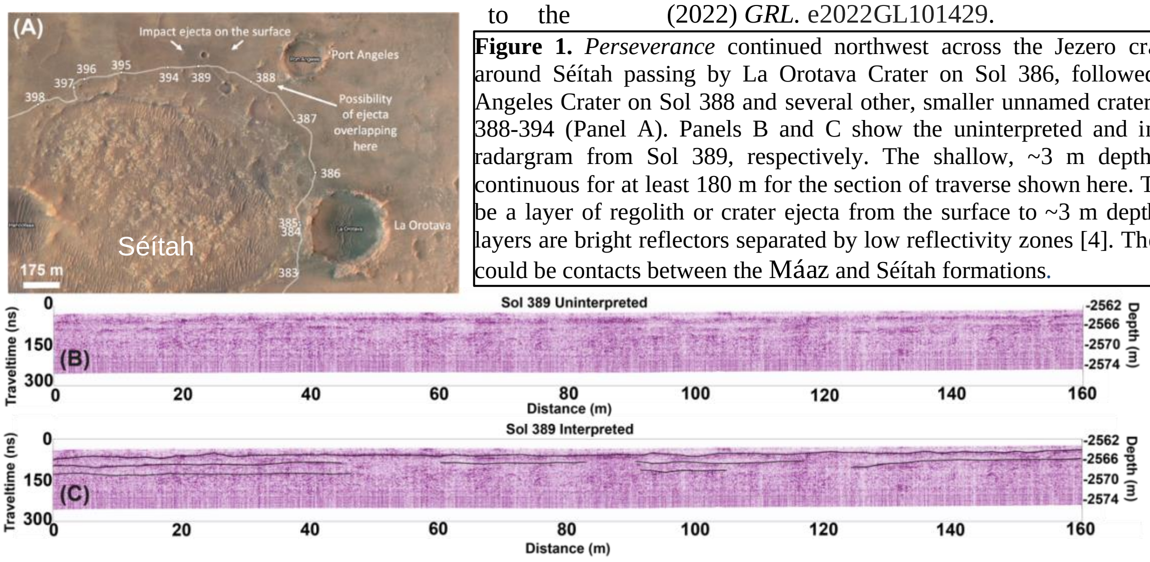

Figure 1. *Perseverance* continued northwest across the Jezero crater floor around Séítah passing by La Orotava Crater on Sol 386, followed by Port Angeles Crater on Sol 388 and several other, smaller unnamed craters on Sols 388-394 (Panel A). Panels B and C show the uninterpreted and interpreted radargram from Sol 389, respectively. The shallow, ~3 m depth layer is continuous for at least 180 m for the section of traverse shown here. This could be a layer of regolith or crater ejecta from the surface to ~3 m depth. Deeper layers are bright reflectors separated by low reflectivity zones [4]. These layers could be contacts between the Máaz and Séítah formations.