MECHANISMS FOR THE ATTENUATION OF SHARAD ENERGY. D. E. Stillman and R. E. Grimm, Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, dstillman@boulder.swri.edu.

Introduction: The objective of the 20 MHz Shallow RADar (SHARAD) instrument on Mars Reconnaissance Orbiter was to detect subsurface reflectors up to 1 km below the martian surface [1]. In practice, reflections from such depths are evident only in ice-rich sediments [2-5]. Over most of the surface of Mars, the only detected reflection is that of the planetary surface itself, and where reflections from the subsurface are detected, they are rarely more than 100 m deep. The general lack of subsurface reflectors on Mars is not likely an indication that the shallow interior is devoid of structure and stratigraphy, as martian imagery has revealed individual lava flows and sedimentary beds that are typically meters to many-tens of meters thick [e.g., 6-9]. Therefore, subsurface structure is not detected due to the larger than expected radar attenuation. This loss is due to some combination of intrinsic absorption of radar energy and volume scattering. We have investigated the origin of radar attenuation on Mars by qualitative association of radar reflectivity with surface geology and by quantitative assessment of absorption and scattering losses.

SHARAD Results: Analysis of SHARAD data was restricted to the northern plains because stratigraphy is better defined there and surface scattering (clutter) is smaller than for the southern cratered highlands. A strong correlation has been found between subsurface reflectivity and the geologic map of the northern plains by Tanaka and co-workers [10].

To demonstrate this correlation the SHARAD results and the geologic map were cross-classified according to the radar response and geological nature of surface units. <u>Abundant Reflectors</u>, <u>Occasional Reflectors</u>, and <u>No Reflectors</u> were used to categorize geologic units in which >50%, <50%, and none of the radargrams in that unit, respectively, showed subsurface reflections. Geological unit descriptions [10] were distilled into three categories: <u>Ice-Rich</u>, <u>Pristine Volcanic</u> – no description of water alteration, and <u>Water Altered</u> – formed by or having been modified by water in fluvial, lacustrine, or periglacial processes (Fig. 1).

Reflector abundance correlates strongly with age and geological unit description (Fig. 1). Remarkably, there are no reflections in any of the units classified as water altered. Pristine volcanics span the full range of reflector occurrence, with the youngest Amazonian units having abundant reflectors, older Hesperian units have occasional reflectors, and the oldest Noachian units having no reflectors. The ice-rich polar-cap units are young and have abundant internal and/or basal reflections [2-5].

SHARAD Adsorption Rate: The weakest reflectors we could interpret had a strength of 19 dB (Campbell et al. [11] interpreted down to ~16 dB). The shallowest reflector interpreted by both Campbell et al. [11] and us had a two-way traveltime of ~0.38 μs. Radar energy can also be lost as not all of the energy at an interface is reflected. However, under the best-case scenario (greatest reflected energy) no energy can be lost due to constructive interference. This occurs if there are two layers with a dielectric constant ε‘ of 4 (4 is the lowest ε‘ of a rock) separated by an intermediate layer that is 1.7 m thick and has a ε‘=9 (9 being the highest ε‘ of dry rock). If the ε‘=9 layer was at a depth of 28.5 m (two-way traveltime of 0.38 μs) then the subsurface of Mars must attenuate at least 19 dB of energy so that it is undetectable by SHARAD. Therefore, the maximum attenuation rate of the martian subsurface is 0.33 dB/m. This rate makes the attenuation of Mars between that of the Earth and the Moon.

Absorption Losses: Absorption losses are controlled by the magnetic and/or electrical properties of the subsurface. Magnetic losses of several percent magnetite could only cause about 0.03 dB/m of loss at SHARAD frequencies [12]. The electrical properties are determined by mineralogy and the presence and state of water. Most truly dry basaltic minerals have very low electrical losses (~0.02 dB/m) [12-13].

We believe that the most likely candidate for causing absorption of the SHARAD signal is adsorbed water. High-surface area minerals such as smectites can hold significant quantities of adsorbed water. Depending on humidity, 1-3 monolayers of adsorbed water can exist in the Martian environment. Adsorbed water attenuates radar energy via a low frequency dispersion (>1 monolayer) and a rotational dielectric relaxation (>2 monolayers) [14-16].

To determine how much adsorbed water is necessary to create the radar absorption detected by SHARAD, we mixed different amounts of a Ca-montmorillonite with a fine-grained sand (Fig. 2.). We then measured the frequency and temperature dependent electrical properties over a range of frequencies and temperatures. We found that by adding >1M Cl that the radar attenuation increases by 50% (Fig. 2). Furthermore, $CaCl_2$ creates slightly more loss than NaCl and SO_4 salts do not enhance the loss from that of deionized water.

Assuming three monolayers of ≥1 M $CaCl_2$ salt and a subsurface temperature of -65°C, smectites at ~12 v% or surface area of ~47 m^2/g are needed to fully attenuate the radar energy under the best-case scenario. If adsorbed water is deionized, then smectites at ~17 v% or surface area of ~74 m^2/g are needed to fully attenuate the radar energy. As this loss is temperature dependent, fewer high surface area minerals are needed if the subsurface is warmer than the average surface temperature as has been observed on the Moon [17].

Scattering Losses: To calculate scattering losses, we used the classical, single-scattering Born approximation (Fig. 3) [18]. At 20 MHz, scattering is maximized for heterogeneity scales of a few to several meters, and requires peak density contrasts up to 0.4–0.6 g/cm^3 to produce the maximum attenuation necessary for Mars. This is consistent with either lithologic variations or fractures filled with unconsolidated material. Alternatively, strong lateral variations much larger than a wavelength (~6 m in the ground), but smaller than the Fresnel zone (~3-6 km)—at scales of hundreds of meters—could make the returned energy incoherent. By contrast, the radar-transparent units must have wavelength-scale density contrasts <0.05 g/cm^3 and coherence within geological units on a scale of kilometers.

Conclusions: We have determined that 0.33 dB/m is the maximum radar attenuation rate needed to obscure the subsurface structure over most of Mars. We cannot discriminate between scattering and adsorption losses. However, the range of reflections in pristine volcanic units shows that as these units become more fractured with time, they attenuate more energy due to scattering. The correlation between the lack of reflections and water altered units indicates that these units have been mineralogically altered and contain high-surface area minerals, which have 3 monolayers of adsorbed water. If radar absorption due to adsorbed water is contributing to at least half of the attenuation, then there is a global equivalent layer of ~1 m of adsorbed water in the top tens of meters of Mars.

References: [1] Seu et al. (2004) *Planet. Space Sci.*, 52, 157-166. [2] Phillips, R.J. et al. (2008) *Science*, 320, 1182. [3] Holt, J.W. et al. (2008) *Science*, 322, 1235. [4] Plaut, J.J. et al. (2009) *JGR*, L02203. [5] Putzig, N.E. et al. (2009) *Icarus*, 204, 443-457. [6] Malin, M.C., et al. (2000) *Science*, 290, 1927 [7] Malin, M.C., et al. (2003) *Science*, 302, 1931 [8] Beyer, R.A. and A.S McEwen (2005) *Icarus*, 179, 1-23. [9] Keszthelyi, L., et al. (2008) *JGR*, 113, E04005. [10] Tanaka, K.L. et al., *U.S. Geol Survey*, Scient. Invest. Map 2888, 2005. [11] Campbell, B. et al. (2008) *JGR*, 113, E12010. [12] Stillman, D.E. and G. R. Olhoeft (2008) *JGR*, 113, E2977. [13] Gueguen Y. and V. Palciauckas, (1994) *Intro to the Phys. of Rocks*, 392 pp. [14] Jonscher, A. K. (1978) *Phil. Mag. B.*, *38*, 587. [15] Ngai, K. L.; White, C. T. (1979) *Phys. Rev. B. 20*, 2475. [16] Bergman, R. et al. (2000) *J. Chem. Phys. 113*, 357. [17] Carrier, W.D., III, Olhoeft, G.R., and Mendell, W., (1991) *Lunar Sourcebook*, 475-594. [18] Van Hove, L., (1954) *Phys. Rev.* 95, 249-262.

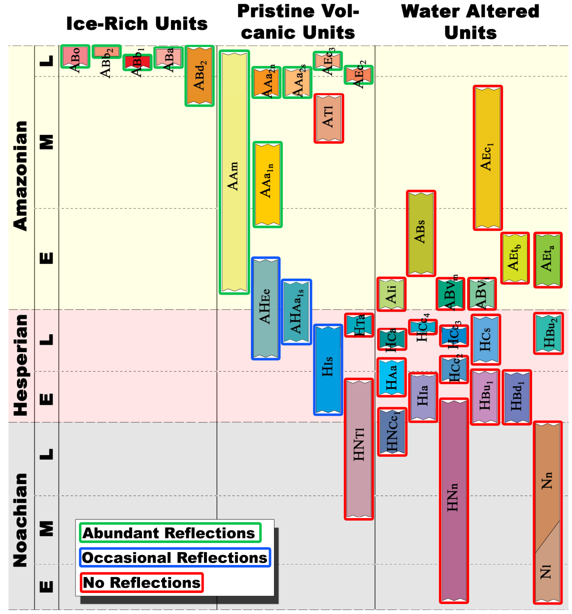

Figure 1. Geologic unit ages with outline colors indicating occurrence of reflections. Almost all of the youngest volcanic units have abundant reflections. No water altered units have reflectors. Modified from [10].

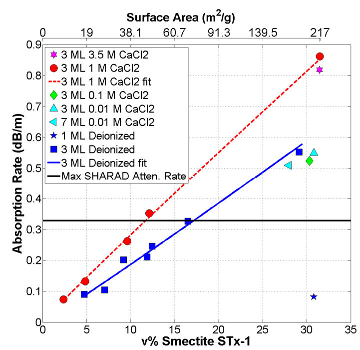

Figure 2. Absorption rate of SHARAD energy at -65°C with 1-7 monolayers (ML) with differing amounts of $CaCl_2$. $CaCl_2$ concentrations of >1M with 3 ML lead to a 50% jump in the absorption rate. As the number of monolayers is increased to three, the absorption rate also increases. However, at >3 ML the water turns to ice is no longer absorbed, thus leaving the absorption rate unchanged.

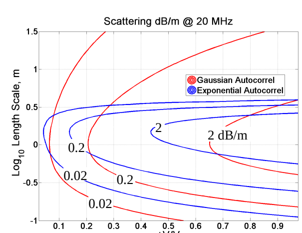

Figure 3. Born scattering at 20 MHz for two different autocorrelation func-tions. Meter-scale heterogeneity with ~30% velocity variations (~40% differences in dielectric constant) yields attenuation in radar-opaque Mars units, ~0.33 dB/m. The same loss can be achieved away from the optimum scatterer size with larger velocity contrast. Velocity contrasts in radar transparent units are restricted to a few percent at meter scale or several tens of percent at decimeter scale.