ANOMALOUS CRATERS IN RADAR AND INFRARED OBSERVATIONS: FORMATION AND EVOLUTION. Wenzhe Fa[1] and Vincent R. Eke[2], [1]Institute of Remote Sensing and Geographical Information System, Peking University, Beijing 100871, China (wzfa@pku.edu.cn), [2]Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK (v.r.eke@durham.ac.uk).

Introduction: Impact craters are the most dominant features on the Moon's surface. Craters over the polar regions, if permanently shaded from direct sunlight, can form cold traps where water ice could remain stable over geologic time [1]. Understanding the formation mechanism and evolution of impact craters provides important clues about lunar chronology, interior structure, polar microenvironment, and impactors in the early inner solar system.

The recent Miniature Radio Frequency (Mini-RF) radars found a class of anomalous craters with high circular polarization ratio (CPR) in their interior but not exterior to their rims [2, 3]. Most of these craters contain permanently shadowed regions (PSRs), potentially indicating that polar anomalous craters are overabundant. Based on their correlation with the locations and distributions of PSRs and water equivalent hydrogen (from neutron data), these anomalously high CPRs were interpreted as originating from water ice deposits [2, 3]. However, radar anomalous craters were also found over non-polar regions, where water ice cannot exist. Recent studies also showed that the high CPRs of non-polar (and possibly polar) anomalous craters are most probably caused by surface and subsurface rocks [4], with high CPR regions tending to be located on the steep interior crater slopes [5]. In addition, all the previous studies are only for a subset of impact craters, and are hence not exhaustive. This unresolved controversy provokes many questions, which require a systematic analysis of multiple global datasets.

Data and Methods: In our study, we analyzed the Lunar Reconnaissance Orbiter (LRO) Mini-RF opposite sense circular polarized backscatter (OC) and CPR, surface topography and slope from the LRO Lunar Orbiter Laser Altimeter (LOLA) observations [6], and the surface meter-scale rock abundance (RA) derived from Diviner infrared observations [7].

We processed 6818 tracks of Mini-RF level 1 raw data using the USGS Integrated Software for Imagers and Spectrometers (ISIS3). We orthorectified the raw image to remove the parallax displacement using the LOLA digital elevation model (128 pixels/degree). We then made four controlled global mosaics with both west- and east-looking directions, for both OC and CPR, with a spatial resolution of ~100 m/pixel.

Using the high resolution topography data and a hydrological algorithm [8], we found a set of 4030 impact craters with diameters between 2.5 and 23 km. We also analyzed 5465 impact craters with diameters between 8 and 20 km from the lunar crater catalog LU78287GT [8]. For each crater, we extracted surface topography, slope, OC, CPR, and RA for regions from the crater center to 1.4 times the crater radius. Since pixel OC and CPR values are generally not Gaussian distributed and have long tails, their median values are used as a more robust measure than the mean pixel value. In addition, we only considered well-sampled craters with data coverage larger than 90%.

Results and Discussions: In CPR and RA images, for the interior and exterior regions, young fresh craters usually have high CPR and RA, whereas old craters are characterized by low CPR and RA values. Anomalous craters can be regarded as an intermediate class, where interior CPR or RA is larger than that of the exterior region. We choose to define CPR-anomalous craters as those with a median interior CPR that is at least ΔCPR=0.1 greater than the exterior region. RA-anomalous craters have ΔRA>0.01. With these definitions, most CPR-anomalous craters are also RA-anomalous. For typical CPR-anomalous craters, the largest CPR occurs over the steepest slopes [5], where rock abundance is also the highest.

Fig. 1a shows the distribution of CPR- and RA-anomalous craters. RA-anomalous craters are mostly located in the maria, whereas CPR-anomalous craters are distributed more uniformly across the lunar surface. The dichotomy in the distribution of RA-anomalous craters indicates that the regolith in the highlands is much thicker than that in the maria, based on the excavation depth and diameter of the craters studied.

The depth/diameter ratio of a crater can be used to indicate its relative age, with larger values for younger craters. Fig. 1b shows the CPR difference between the crater interior and exterior as a function of the depth/diameter ratio for all the studied craters. As can be seen, young fresh craters usually have a large CPR difference. For older craters with small depth/diameter ratios, CPR values within and outside the crater rim are roughly equivalent, and both are low.

Fig. 1c shows the areal crater density as a function of latitude for all craters with diameters of 8–20 km, the subset that are well-sampled with Mini-RF data, and the subset of those that are CPR-anomalous. The ratio of these latter two curves is shown in Fig. 1d, indicating no statistically significant evidence of polar CPR-anomalous craters being overabundant.

In some cases, CPR-fresh craters are RA-anomalous. Also, it is often the case that no surface rocks are detected in either the interior or exterior regions of CPR-anomalous craters. Since Mini-RF is sensitive to subsurface rocks at a depth of ~1 m, these two classes of craters indicate that subsurface rocks contribute significantly to the received radar echo.

Based on the statistics of fresh, anomalous, and old craters, the presence and evolution of meter scale rocks associated with impact craters can be studied. A newly formed crater possesses surface and subsurface rocks both inside and outside its rim, and has high CPR in the radar image. As time goes on, both surface and subsurface rocks break down due to micrometeorite bombardment. As mass wasting depends largely on surface slope and because the inner wall slope is much larger than the outer wall slope, surface rocks within craters are more readily refreshed than those outside the crater rim. Thus, craters pass through RA-anomalous and CPR-anomalous phases. Due to self-shielding by the lunar regolith, subsurface rocks break down more slowly than surface rocks. This is the reason why in some cases a RA-anomalous crater looks fresh in the CPR image. When a crater is old enough, both surface and subsurface rocks break down, and the crater looks "old" in both the CPR and RA images. Using the survival time of meter-scale rocks [10] and craters with known absolute ages [11], we found that RA-fresh craters can last for 300 Myr whereas the CPR-anomalous stage can last for 3 Gyr.

Conclusions: In this study, we systematically analyzed the statistics of impact craters in radar and infrared images. Our results show that most CPR-anomalous craters are relatively young with a large depth/diameter ratio, and that CPR-anomalous and RA-anomalous craters are just a stage of normal crater evolution. Statistical results indicate that there is no apparent difference in CPR between the polar, potentially icy, and non-polar, not icy, craters. For craters with diameter between 8 and 20 km, polar radar anomalous craters are not overabundant. These findings provide valuable information for understanding the cratering process and the evolution of the lunar surface.

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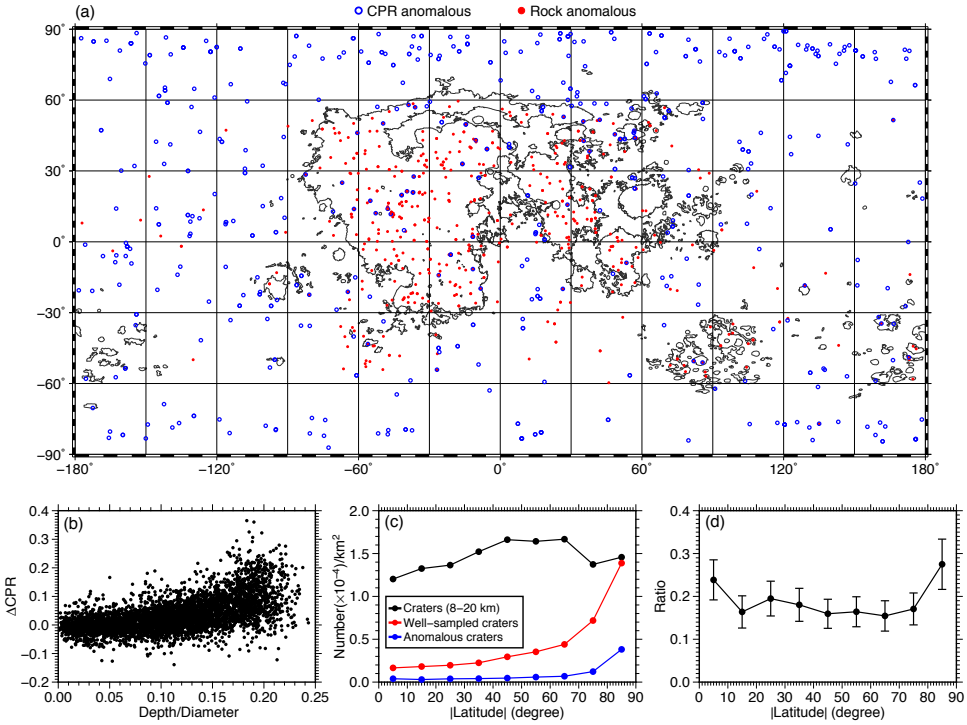

Figure 1. (a) Distribution of CPR-anomalous craters (blue) and RA-anomalous craters (red). The black curves outline the boundary of the mare basalt from the USGS. (b) CPR difference between interior and exterior as a function of depth/diameter ratio. (c) Areal density of craters with: 8<diameter/km<20 (black), Mini-RF coverage>0.9 (red), coverage>0.9 and ΔCPR>0.1 (blue). (d) Fraction of well-sampled craters that are CPR-anomalous as a function of latitude.