Orientale Secondary Craters: Insights Into Orientale Impact Parameters and the Largest Secondary Crater Size of the South Pole-Aitken Basin Event. Dijun Guo[1, 2, 3], Jianzhong Liu[1], James W. Head[3], M. A. Kreslavsky[4] [1]*Center for Lunar and Planetary Science, Institute of Geochemistry, Chinese Academy of Sciences, 99 Lincheng West Road, Guiyang 550051, China (liujianzhong@mail.gyig.ac.cn).* [2]*University of Chinese Academy of Sciences, Beijing 100049, China.* [3]*Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA (james_head@brown.edu).* [4]*Earth and Planetary Sciences, University of California – Santa Cruz, 1156 High Street, Santa Cruz, CA 95064 USA*

Introduction: Secondary craters (or secondaries) represent the craters formed by the impact of fragments ejected from the primary impact , generally occuring beyond the continuous ejecta deposit [1-3]. As one of the youngest lunar basins, Orientale basin has the best-preserved secondary craters and other ejecta facies among basins of comparable scale [4, 5]. The characteristics and distribution of its secondaries can form a paradigm for other large basins on the Moon. Because post-basin mare lava flooding to the east of Orientale has buried original ejecta deposits, secondary crater distribution provides an additional approach to recognize the distribution of Orientale ejecta, from which the parent impact parameters, such as projectile approach direction and angle can be speculated.

Detecting Orientale secondary craters: We report on our investigation of Orientale secondary craters carried out in the area as far as 6 R (R = Orientale radius) from the Orientale basin rim, i.e. Monte Cordillera. To display better the spatial distribution of secondaries, the area of investigation is divided into small annular sectors with each annular sector being half of an Orientale radius wide in radial direction and 20 azimuthal degrees wide in the concentric direction (Figure 1).

We identified 2728 secondary craters with diameters (D) ranging from 2.14 km to 27.09 km in a total area of ~1.66×10^7 km^2 (Figure 1). The results suggest that secondaries are concentrated in the northwest and their diameter decreases as distance increases. There are 47 secondary chains identified (Figure 1), whose lengths range from 27 km to 410 km, and are 128.7 km long on average.

Orientale impact scenario: The diameter and density of secondaries are inhomogeneous with azimuth angle, indicating the heterogeneities of ejecta deposits with respect to azimuth (Figure 1, Figure 2). It is obvious that mean diameter does not closely relate to azimuth, while the density dramatically varies in different sectors.

Impact direction

As show in Figure 2, the density of secondaries can be subdivided into five regions: the northwest high-density region (H) and medium-density region (M1), the southwest medium-density region (M2), the wide low-density area (L1) in the east side and the other narrow low-density area (L2) in the west. H region (305° to 330°) and M2 region (200° to 230°) show an approximately bilateral symmetry, indicating the downrange of Orientale impact direction was about the azimuth of 265º. Considering that the density of M1, next to H, is apparently higher than most of the other regions, and that the existence of the very low density area around 240º, the downrange direction of impact could be south to azimuthal 240º. In conclusion, the Orientale impact downrange direction could be 240º to 265º, therefore the uprange could be 60º to 85º (Figure 2)

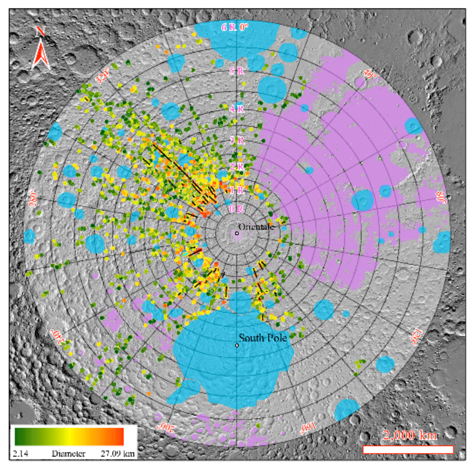

Figure 1. Locations of 2728 identified Orientale secondary craters; red color indicates larger diameter and green color represents smaller diameter. Secondary chains are marked with short black lines radial to Orientale. The purple shaded area designate that mare basalt was emplaced in these regions. Blue shaded areas are interference zones where the secondaries are subdued or the light condition does not support crater identification. Basemap is hill-shade image from LOLA. The map is in stereographic auxiliary projection centering at Orientale center (95º W, 19º S).

Impact angle

The secondary crater density discrepancy at different azimuthal angles implies that the pattern of Orientale ejecta is between the planform characteristics of (1) offset and concentrated cross-range and (2) forbidden zone [6, 7]. On the Moon, the transition angles of offset, forbidden zone and butterfly are 45°, 25° and 10° respectively, but the transition angle of offset and concentrated cross-range is unknown [6], therefore the incidence angle of Orientale impact is in the range of 25 to 45 degree. Considering the incidence angle for offset and concentrated cross-range ejecta planform is lower than the gentle offset planform, the upper limit of incidence angle could be smaller than 45°.

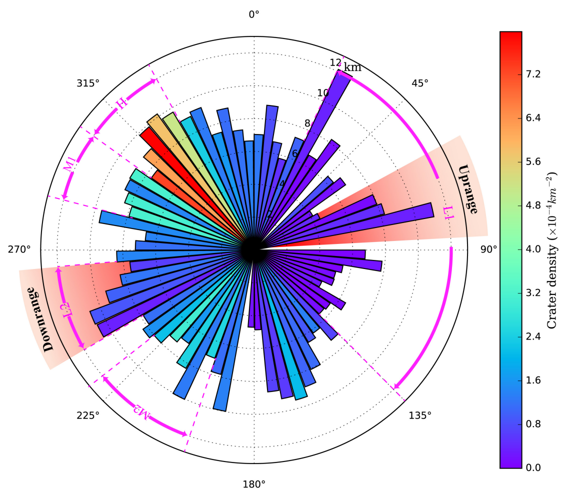

Figure 2. Density and average diameter of secondaries located in different azimuthal bins. Each bar represents a sector of 5 azimuthal degrees wide in a concentric sense. The color of the bar represents density, and the length represents average diameter. H-high density, M1 and M2-medium density, L1 and L2-low density. The azimuth range of the estimated uprange and downrange of Orientale basin impact directions are shown.

Estimate the largest secondary craters of South Pole-Aitken basin: Several previous studies of secondary craters [1, 4, 8, 9] make it possible to obtain the scaling relationship of the largest secondary craters and their parent craters on the Moon, as shown Figure 3. Because the ratio of largest secondary crater diameter (D_{LS}) to parent transient cavity diameter (D_{PT}) decreases with increasing in primary diameter, the largest secondary diameter versus parent diameter is separated into two groups (shown Figure 3). The relationship of D_{LS} and D_{PT} for large craters is $D_{LS} = (1.28 \pm 0.947) D_{PT}^{0.47 \pm 0.118}$ (Figure 3), which can be used to estimate D_{LS} of the heavily degraded South Pole-Aitken (SPA) basin. Estimates of the transient cavity diameter of the SPA basin ranges from 840 km to 2500 km according to different estimations, corresponding to a diameter range of the largest secondary crater of 29.7 km to 49.5 km. The study of Garrick-Bethell and Zuber [10] reveals that the major axis of SPA outer ring is 2400 km, therefore we infer that the largest secondary crater of South Pole-Aitken basin is not greater than 40 km in diameter.

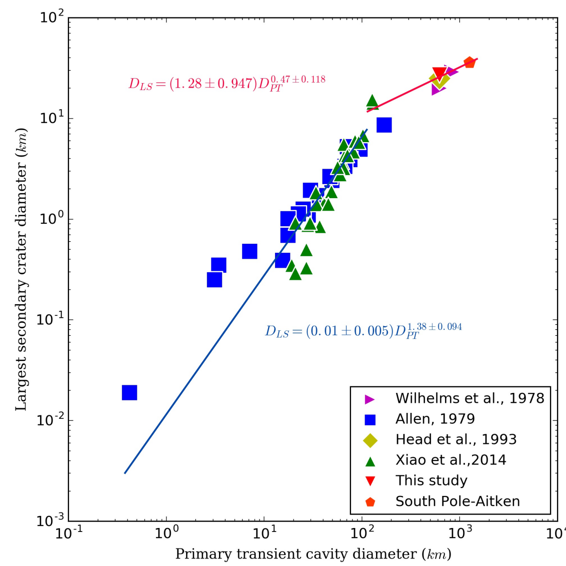

Figure 3. The largest secondary crater diameter versus transient cavity diameter of the parent crater and power law fits. Power law fits are made separately for small primary craters and large primary craters. The transient cavity diameter of the South Pole-Aitken basin ranges from 840 km to 2500 km, corresponding to a diameter range of the largest secondary crater from 29.7 km to 49.5 km.

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