IMPACT EJECTA TEMPERATURE PROFILE ON THE MOON – WHAT ARE THE EFFECTS ON THE AR-AR DATING METHOD? V. Fernandes[1], N. Artemieva[2,3] , [1]Museum of Natural History 10115 Berlin, veraaf-ernandes@yahoo.com, [2]Planetary Science Institute 85719 Tucson, [3]Institute for Dynamics of Geospheres 119334 Moscow, artemeva@psi.edu

Introduction: The $^{40}Ar/^{39}Ar$ method is widely used for the acquisition of impact related cooling ages of a variety of lunar rocks. Several of the Apollo, Luna and lunar meteorite samples dated (e.g., [1-3]) have demonstrated that there is a decoupling between K-Ar reset ages and their shock related petrographic features: partial to total resetting of the K-Ar system occur even at low shock pressures (**Fig. 1**) when post-shock temperature increase is also low (~100ºC; [6&7]). Therefore, the $^{40}Ar/^{39}Ar$ data suggest that the Apollo samples, after an impact event, were kept in a warm environment for a certain amount of time which permitted the partial to total resetting of the K-Ar clock. The most likely feature for this warm environment is the impact ejecta, which in the case of the impact basins formed during the period from ~4.5 to ~3.9 Ga (e.g. Imbrium) could be hot and correspond to large volumes of material being displaced globally. Here we present preliminary model results for the formation and evolution of shock-heated ejecta blanket produced during a large impact event on early-hot and present-cold Moon, and its effects on pre-existing cold rock fragments.

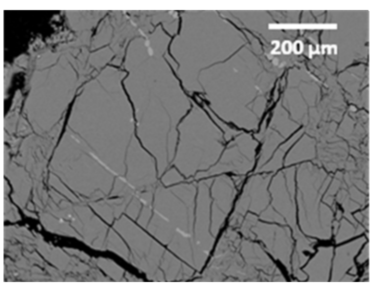

Fig.1 Apollo 16 samples 60025 is a cataclastic ferroan anorthosite showing shock-related fractures in plagioclase (e.g. fractures) but no thermal metamorphism related features. The Sm/Nd age is 4.44±0.02 Ga [4] or 4.36±0.003 Ga [5] and the $^{40}Ar/^{39}Ar$ age suggests a thermal disturbunce at ~4.2 Ga [e.g., 1&3].

Numerical model: We model oblique impacts on the Moon with the 3D hydrocode SOVA [8] complemented by the ANEOS equation of state for geological materials [9]. We use two thermal profiles within the target: cold-present-Moon with a thermal gradient of 2 K/km, and hot-ancient-Moon with a thermal gradient of 15 K/km [10]. To define ejecta distribution on the surface, we use a method of ballistic continuation on a sphere [11]. The evolution of post-depositional temperature profile within the ejecta blanket is estimated via one-dimensional thermal conductivity equation.

Ejecta distribution on the Moon and temperature of the ejecta blanket. At any distance from the crater ejecta is a mixture of materials compressed to various shock pressures P (from partial vaporization, P>150 GPa, to weakly compressed fragments P<3 GPa and excavated from various depths (**Fig.2**). At distal sites, melt and highly compressed materials from the crust prevail, whereas the near-crater ejecta consist mainly of unshocked materials.

The value of shock pressure coupled with equation of state (EOS) may be used to calculate a temperature increase along the target after the shock wave passage. The final temperature is the sum of the initial temperature, T_0 (which depends on the initial burial depth and temperature gradient of the Moon), and temperature attained due to the shock wave T_{sh}. (which depends on the value of shock compression).

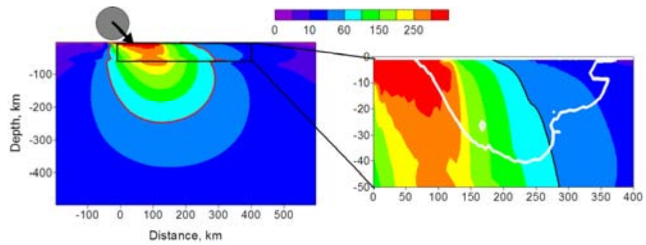

Fig. 2. *Left*: shock compression P (in GPa) within the target after a 100-km-diameter asteroidal impact at 45° (see color legend, the red line corresponds to basalt melting). *Right*: expanded black rectangular box from the left plate showing material ejected at 2 km/s (white line) and compressed to various shock pressures.

Results: At the present-cold-Moon, antipodal ejecta (at 5460 km from impact) have a temperature range of 400-600 K, while proximal ejecta have only slightly elevated T of 250-300 K. If the early Moon was substantially hotter (thermal gradient of 15 K/km during the first 0.2-0.5 Gyr), an average ejecta temperature reaches 600 K at distances > 2400 km from a crater center, and is above 400 K at smaller distances (see **Fig. 3 and 4**).

Immediately after deposition, the ejecta blanket is a mixture of materials with a variety of temperatures – from cold unshocked fragments to high-temperature melt lumps. These temperature-spikes within the blanket are equilibrated quickly due to the heat exchange between hot and cold fragments. Then, the whole layer cools slowly with time. Ejecta cooling time τ after its deposition depends strongly on the ejecta blanket thickness H ($\tau \sim H^2/\alpha$, α is a thermal diffusivity, $\alpha \approx 10^{-6}$ m^2/s), which, in turn, increases quickly with the projectile size D_{pr} increase ($H \sim D_{pr}^3$). Thus, gas losses due to an elevated post-deposition temperature is not as important for small impacts (with fast cooling rate), however it may lead to a partial or total resetting of the K-Ar system in large, basin-forming impacts.

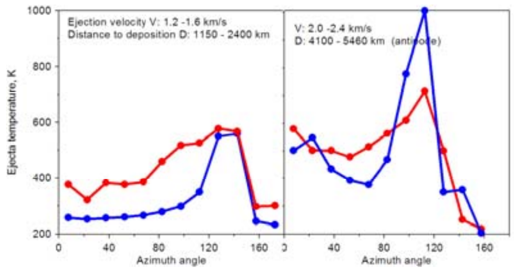

Fig. 3. Temperature within ejecta blanket for different distances from the impact as a function of azimuth (0 correposponds to down-range direction, 180° - to uprange direction). Red curves are for the *ancient-hot-Moon* with high T-gradient. Blue curves - for the *present-cold-Moon*. Materials compressed above vaporization (~200 GPa) were excluded as they were deposited non-ballistically (for this reason ejecta temperature for the cold Moon may be higher than for the hot Moon).

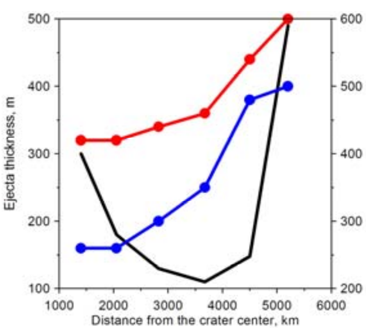

Fig.4. Average azimuth ejecta blanket thickness (a black line, left axis) and average temperature (red line – hot-Moon, and blue line – cold-Moon, right axis) for a 100-km-diameter impactor. The Imbrium impactor was 1.3-1.8 times larger in diameter, i.e., the Imbrium ejecta could be 2.2-8 (cubed diameter) times thicker.

Imbrium (~3.85 Ga) ejecta blanketed the area extending for more than 800 km outward [13,14]. Many of the Apollo lunar samples are believed to be contaminated by or are Imbrium ejecta, e.g., [15]. For this basin, a 769 km transient cavity diameter was estimated [16]. Although it is quite difficult to estimate a projectile diameter for this large basin, it would be in the range of 130-200 km, depending on the impact angle, impact velocity, and thermal gradient within the Moon at the moment of the impact. Nonetheless it is plausible to suggest that during this event temperatures within the ejecta blanket could have been sufficient to have cause the K-Ar resseting of unshocked (and cold) rock material that was included within it.

Conclusions and future work: The K-Ar dating system is the most susceptible of the isotope pairs to increases of the thermal gradient and the length of time the rock is maintained at that temperature. The model presented here, enables to better understand the temperature change over time within the large ejecta blankets originated by impact basin forming events. These temperatures/times will then be used to better understand the Ar-diffusion within lunar rock fragments.

Most, if not all, of the samples in the present lunar sample collection have been at some time, after crystallization, under a *warm-hot* environment which partially or totally resets the K-Ar clock. Such change in temperature on the Moon was in most cases due to impact events. Depending on the proximity to the crater, lunar samples present impact related shock features, e.g., from low (P = ≤20GPa) to high (P = ~55 GPa) pressures: fractures, undulatory and/or mosaicism extinction, cataclasis, 120° grain boundary, recrystallization; **Fig. 1**). Together with the increase in shock pressure, there is a correlated increase in shock-related temperature [6,7]. However, lunar samples indicate a decoupling between petrographic shock pressures and their K-Ar clock: low-P features and reset K/Ar. The likely reason is that low-shocked samples resided within a *hot-warm* ejecta blanket. As shown in the model above, temperatures within an ejecta blanket during the *early-hot-Moon* can vary from 600-700 K (327-427°C). Considering that plagioclase closure temperature is <573K [17], a rock fragment kept at 600-700 K for >20 y within an ejecta blanket will likely have its K-Ar systematics partially to totally [e.g., 18].

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