METEORITES FROM MARS – CONSTRAINTS FROM NUMERICAL MODELING. N. Artemieva and B. Ivanov, Institute for Dynamics of Geospheres, RAS, Moscow, nata_art@mtu-net.ru, ivanov@lpl.arizona.edu

Introduction. We continue numerical modeling of the SNC meteorites [1,2] and compare our results with mineralogical, petrological and geophysical data.

Numerical modeling of meteorite ejection. Oblique impacts are simulated with a three-dimensional version of the SOVA code [3], coupled to ANEOS-derived [4] equation of state tables. The later stage of ejecta motion in a disturbed Martian atmosphere is described by multi-phase hydrodynamics [5]. Each particle is characterized by its individual parameters (mass, density, shape, position, velocity) and exchanges momentum and energy with a surrounding vapor-air mixture.

Pressure versus ejection velocity. Fig.1 shows the pressure and ejecta velocity distributions with respect to the initial position of the target material, reconstructed with the tracers. The intersection of the pressure contours (50 GPa) with the velocity contours (5 km/s) gives a proper presentation of the SNC-source. The material from the uppermost layer has the highest ejection velocity up to 10 km/s and the lowest shock compression (5-10 GPa, not less!). Burial depth does not esceed 10% of the projectile diameter, or 40 m (400-m-diameter projectile with impact velocity of 10 km/s, final crater diameter of 2.7 km).

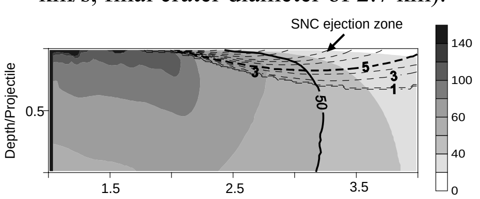

Fig.1 SNC ejection zone; gray scale is for maximum P, dashed lines – V_{ej}.

Size-distribution of fragments. The most likely fragment size to be formed under loading at a constant strain rate is defined by Grady-Kipp distribution [6]. Alternatively, an average fragment size may be connected with ejection velocity [7]; or standard cumulative distribution of fragments $N=CM^{-b}$ with the maximum size defined by the value of maximum compression [8]

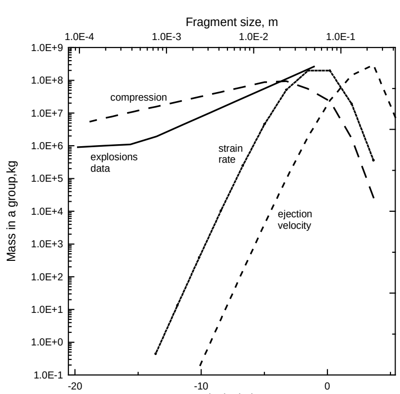

Fig.2 Differential distribution of ejected fragments

In atmospheric effects modeling we consider three variants of the size-distributions for the same final crater of 2.7 km: (I) the Grady-Kipp distribution maximum at 24 cm (the largest fragment is 75 cm) – roughly corresponding to the distribution based on maximum ejection velocity in Fig. 2; (II) the maximum fragment of 24 cm – as in Fig.2 for the strain rate defined distribution; and (III) the maximum at 4 cm and with the largest fragment size of 14 cm – an approximately pressure-defined distribution.

Atmospheric deceleartion. The atmospheric losses are substantial in the case of the "small impact" scenario with final crater size of about 3 km [2]. However, ~20-40% of the largest fragments (20 cm and larger) survive and escape Mars. The total mass of escaping fragments is $2.5 \cdot 10^8$ kg for the variant I, 10^7 kg for the variant II, and only 70 kg for the variant III.

Shock metamorphism in SNC meteorites. New shock wave barometry data [9] show that all known Martian meteorites are shocked in the range from 10 to 45 GPa with the group of clinopyroxenites (Nakhlites) being most weakly shocked (10-20 GPa), the basalts clustering at 28-31 GPa and at 42-45 GPa, and the lherzolitic rocks at 43-45 GPa. These shock effects can be attributed to one specific event in each case (with the single exception of ALH84001) The observed shock pressure range is essentially confirmed by our computer code calculations – we do not have lightly compressed (<10 GPa) escape fragments.

Burial depth. The complete lack of 2-π cosmic ray exposure argues that the SNC meteorites came from at least 1m depth [10]. Mineralogical and petrological studies of the SNC microstructures [11-12] allow to derive the maximum burial depth in a parent magma chamber of 30m for all Nakhlites, <3 m for the majority of Shergotties. A rather low cooling rate in Shergotty and Zagami does not necessarily mean a substantially deeper magma structure, but may be explained by the late (after partial cooling) intrusion of a dyke. In our "small impact" scenario the maximum burial depth for escaping ejecta is 40 m.

Pre-atmospheric size. Calculated epithermal neutron fluxes in a few Martian meteorites [13] allow an estimation of the minimum pre-atmospheric radius in the range of 22-25 cm, with a minimum mass of 150-220 kg. Zagami is the largest single individual Martian meteorite ever found, with a mass of 18 kg. Nakhla was disrupted during the atmospheric entry into the ~40 stones, with a total mass of about 10 kg. Standard estimates of the mass loss (ablation and fragmentation) during the atmospheric passage [14,15] show that stony meteorites entering the atmosphere with a velocity of 18 (13) km/s lose ~90 (60) % of their initial mass. Thus, we can expect that pre-atmospheric mass of the largest SNC meteorites is in the range 50-200 kg in agreement with our estimate: only 20-kg-fragments (and larger) are not decelerated by the martian atmosphere.

Temperature increase. We make accurate temperature estimates based on the experimental EOS for geological materials [16,17]. Dunite and pyroxenite give the smallest values of post-shock temperatures. ALH84001 (orthopyroxenite), compressed at ~35-40 GPa has a maximum temperature increase during the shock of ~112 -231 K (for P=30 and 40 GPa respectively) and a long-lasting post-shock temperature increase of about ~94-122 K. Taking into account the initial subsurface temperature on Mars, we have a maximum temperature in the range of 32-151°C and a post-shock temperature in the range of 14-42 °C. Weiss et al. [18], analyzing remnant magnetization, argued that this meteorite has never been heated above 40°C. It means that the value of shock compression (purely defined for this sample) was close to its lower limit. In summary, we can expect the highest post-shock temperature increase (above 350 K) for basaltic and lherzolitic shergottites (shock compression up to 45 GPa), and the lowest increase (probably a few degrees) for nakhlites (shock pressure 9.5-17 GPa).

Lunar meteorites versus Martian meteorites. We use similar procedures to model lunar meteorites and find that delivery efficiency of "meteorite production function" in the single event on the Moon is substantially higher than on Mars. However, an amount of lunar and martian meteriutes are comparable. Processes, defining meteorite delivery from Mars and Moon to the Earth, are summarized in the Table:

	Mars	Moon
Escaping ejecta/projectile	0.05	0.5
Atmospheric "permeability"	0.3	1
Delivery to Earth	0.1	0.3
Total efficiency	**1.5e-3**	**1.5e-1**

Assuming the largest statistically probable impact (3 km-diameter crater on Mars with the projectile volume of 0.004 km^3; 1 km-diameter crater on the Moon - $1.4\cdot10^{-5}$ km^3), we have $6.0\cdot10^{-6}$ and $2.1\cdot10^{-6}$ km^3 of martian and lunar meteorites respectively after the single impact event. Smaller scale Martian impacts can't produce meteorites because of substantial atmospheric deceleration. Hence, the total volume of the SNC meteorites is x4-x8 (number of sampling events), i.e. ~$(2.5\text{-}5)\cdot10^{-5}$ km^3. On the Moon, smaller events also may produce escaping ejecta wuth the total volume of lunar meteoites:

$$V_{lunar} = bV_{\max}\int_0^1 x^{2.84-b}dx,$$ where V_{max} = $2.1\cdot10^{-6}$ km^3 is the lunar meteorite's volume in the the largest impact event during the last 0.1 Myr and b is the slope of size-frequency distribution (SFD) of lunar craters. The integral diverges in the case of $b\geq3.84$. However, in Hartmann's SFD the value of b is 3.82 for the smallest lunar craters and Neukum's SFD estimate is even lower ~3.55 for the craters with <0.1 km <D < 1 km [19]. For this range of b-values V_{lunar}= b/(3.84-b) = (12-190)V_{max} or $2.5\cdot10^{-5}$- $4\cdot10^{-4}$ km^3. Only the largest, most extreme value is an order of magnitude larger than the total volume of Martian meteorites delivered to Earth, while moderate estimates are absolutely comparable with the observed population.

Conclusions. Numerical results are in a good agreement with available geophysical and petrological data. The values of shock and post-shock temperatures are of a crucial importance for the problem of assessing whether viable microorganism transfer can occur between the two planets. A recent publication [20] assumed unrealistically low compression at ejection (~1 GPa), to allow organic molecules survival at the SNC ejection. Our modeling shows that, on one hand, it is impossible to eject material with escape velocity without substantial (>10 GPa) compression in a shock wave, and on the other hand, a temperature increase in meteorites with composition similar to pyroxenite (Nakhla, ALH84001) or dunite (Chassigny) may be well below 100 degrees.

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