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Small asteroid impact and cratering on Mars

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Abstract

The consequences of impact of small stony asteroids (with masses less than 100 t) on Mars surface are investigated. The atmospheric braking is found to be negligible as is the maximal dynamic pressure exerted on the impacting body. In other words, the impactor remains unfragmented until the impact. The resulting crater size depends on the kinetic energy of the impactor and the lithological properties of the Martian surface and shallow crust as well as later atmospheric erosion.

Keywords: Mars, cratering on Mars, meteorite flight

1. Introduction

Mathematical model of a small asteroid dynamics during a flight through the Martian atmosphere determines the final remaining kinetic energy of the impacting body. By calculating the deceleration and the dynamic pressure exerted on the incoming body over the course of its trajectory through the atmosphere, the height at which the largest dynamic pressure is reached, and incoming body's final velocity are determined. Input parameters are the mass of the incoming body, initial velocity vector's magnitude and the angle of entry. Initial height above the ground level (z coordinate in a Cartesian coordinate system fixed at the Mars surface) is set at 100 km, for all simulated cases.

In all flight calculations we used the usual approach: the drag force is calculated through the Newton's drag law, with variable, velocity dependent drag coefficient. Here, we assumed a spherical body and used the coefficient from **(Carter at al., 2009).** For the atmosphere, exponential model with data for the Mars atmosphere was used. All initial calculation parameters are summed up in the **Table 1** and **Table 2**.

However, the bombardment of planetary surface is casual process, nowadays on declining frequency in the whole Solar system, therefore on the Mars as well. This in contrast to the beginning of Solar system's existence when such processes were very frequent and widely varied in numbers and sizes of falling bodies. Back then, Mars played significant role in creation of still existing asteroid belt. In the very beginning, the early bombardment phase took place until 0.5 Ga after creation of the system. Perhaps the most prominent result of this bombardment is the creation of the Moon, after inclined collision of the proto-Earth and Theia. Some calculations (**Petit & Morbidelli, 2001; Kominami & Ida, 2001**) indicated that in this phase of it's development the Solar system included 50-100 planetary bodies with sizes more or less equivalent to the size of Mars. Most of them collided in the first 0.1 Ga and were merged or destroyed (**Lin, 2008**), and the Solar system was left with four present-day terrestrial planets.

The early bombardment period was followed by late bombardment phase, which lasted approx. 0.5-1.0 Ga after the creation of the Solar system. There was no merging or destroying of planets and planetoids, and this phase was characterised by large scale bodies impacts on the existing four planets and the Moon. The most objects, but not all, had their origin in the asteroid belt. Although such impacts were extraordinarily energetic, and often affected the planets' crusts, their impact craters are later eroded and lost. The erosion took place on all terrestrial planets due to early volcanism as well as atmospheric and oceanic processes (Earth, Venus, Mars). The asteroid belt, today located between 2 and 4 a.

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u., played the main role in the late bombardment phase. In the beginning this belt included mass of about 2-3 Earth masses, probably in the form of 20-30 planetoids, ranging in sizes from Moon's to Mars' (**Bottke et al., 2005**). However, the Jupiter, even the Saturn, gravitationally prevented the accretion of planetoids into larger planet(s), assisted with later approaching of the Jupiter to the Sun, which increased the orbital velocities of the belt bodies and pushed them toward inner Solar system (**Bottke et al., 2005**; **Raymond et al., 2007**). When the gravitational balance had been established again, only 1 % of the Earth mass remained in the asteroid belt, still occasionaly ejecting asteroids across the Solar system until today, when the remaining mass is the 0.05 % of the Earth. Many of the asteroids brought water on the planets, and larger planets, like the Earth and Venus, kept it in their oceans. Among the terrestrial planets, only the Earth has one additional process that's changing its shape and is responsible for the destruction of the older surface structures. It is plate's tectonic.

Equatorial diameter (km)	6780
Surface gravity (m/s^2)	3.71
Atmosphere composition (%)	96 CO_2 1.9 Ar 1.9 N_2
Surface atmospheric pressure (Pa)	636
Expected variations of surface pressure (Pa)	400-870
Mean surface temperature (K)	210
Expected variations of surface temperature (K)	130-308
Mean orbital speed (km/s)	24
First cosmic speed (km/s)	3.57
Second cosmic speed (km/s)	5.03
Third cosmic speed (km/s)	34.1

Table 1: Physical characteristics of the Mars

The **Table 1** gives basic physical characteristics of the planet Mars, starting with its diameter and surface gravity. Note that, although Mars is about half the size of the Earth, its surface acceleration is only about one third of the surface acceleration of the Earth. Martian atmosphere is very rare. The surface pressure varies widely depending on the location and the time of the Martian year. Mars is farther from Sun than Earth and is accordingly slower in its orbit. Also, the third cosmic velocity for Mars (the velocity needed for a body to leave the Solar System) is about three quarters of the corresponding velocity for Earth. Combined with a weaker Martian gravity, this results in lower impact velocities for impacting bodies, compared to the Earth. Thus, incoming objects will strike Mars with velocities between about 5 and 58 km/s, compared to 11 to 72 km/s for the Earth.

Asteroid type	Chondritic (stony)
Asteroid density (kg/m^3)	3300
Asteroid mass (kg)	10 - 81920
Angle of entry (towards horizontal, deg)	10 - 90
Incoming velocity (km/s)	10 - 50

Table 2: Physical characteristics of asteroids as used in our calculations.

As stony asteroids are the most common type, the calculations were done for this type of asteroids only, with their physical properties summarized in the **Table 2**. The Martian atmosphere is significantly less dense than the Earth's, thus the resulting drag forces and dynamic pressures are much smaller as well (**Figure 1**). This means that fragmenting of the incoming body is less probable, as also suggested by the results of the calculations.

2. Methods

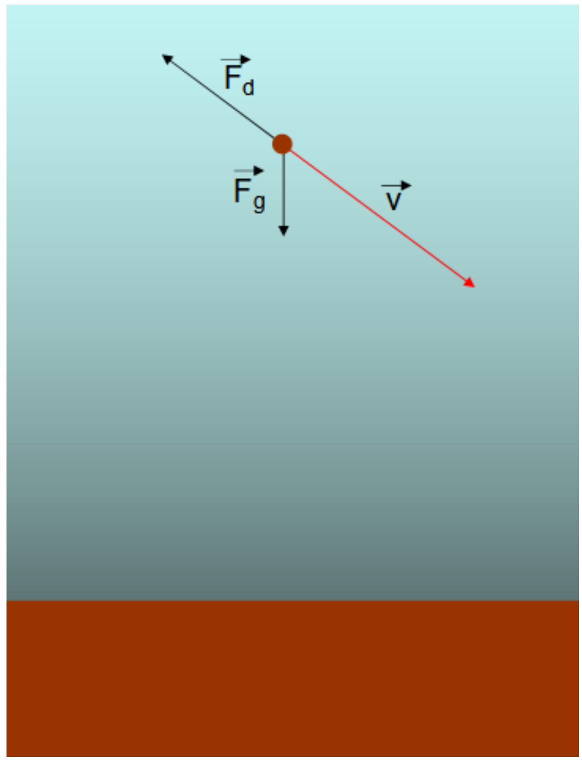

Figure 1: Forces acting on an incoming body in a planetary atmosphere (blue). The asteroid velocity is $\vec{v}$, and is usually specified by its magnitude and the angle of entry (usually measured between the direction of the flight and the horizontal). The body is simultaneously influenced by the gravitational force of the planet, $\overrightarrow{F_g}$ and the drag force $\overrightarrow{F_d}$.

The gravitational force is, to a very good approximation, described by the well known Newton's **Equation 1**:

$$\overrightarrow{F_g} = G\frac{Mm}{r^2}\frac{\vec{r}}{r} \tag{1}$$

Where are:
$\overrightarrow{F_g}$ *is the gravitational force,*
G is the universal gravitational constant,
M is the mass of the planet,
m is the mass of the asteroid,
$\vec{r}$ *is the distance between these two bodies.*

Usually, this formula is rewritten using the surface acceleration $\overrightarrow{a_g}$ as **Equation 2**:

$$\overrightarrow{F_g} = \overrightarrow{a_g}m\frac{r^2}{r_o^2} \tag{2}$$

Where are:
$\overrightarrow{a_g}$ *stands for the surface gravitational acceleration,*
r for the distance between the two bodies and
r_o *is the diameter of the planet.*

The decrease of the gravitational acceleration with distance is often neglected for small distances (compared to the planet's diameter), resulting in a simpler **Equation 3**:

$$\overrightarrow{F_g} = \overrightarrow{a_g} m \tag{3}$$

The drag force imparted on the asteroid inside the Martian atmosphere is given by the Newton's drag law (**Equation 4**):

$$\overrightarrow{F_d} = -\frac{1}{2} c\rho A v \vec{v} \tag{4}$$

Where are:
c is the drag coefficient,
ρ is the density of the surrounding medium (e.g. Martian atmosphere),
A is the cross-sectional area of the incoming body and
$\vec{v}$ is the velocity of the body relative to the atmosphere.

The drag coefficient depends on the shape of the body and varies with the speed to a certain extent. We used data from (**Carter at al., 2009**) for a spherical asteroid. The dynamic pressure is, to a first approximation, equal to the drag force divided by the cross-sectional area of the body moving through the fluid (i.e., atmosphere). Wind is neglected in our calculations as is the planetary rotation.

Under these approximations the model can be reduced to a two-dimensional problem. Calculations are performed in the plane of the meteorite trajectory. The cartesian coordinate system is set up with the x axis horizontal, +x pointing into the direction of the flight. The y axis is vertical, +y pointing up. The equation of motion of the asteroid is now (**Equation 5**):

$$m\vec{a} = m\overrightarrow{a_g} - \frac{1}{2} c\rho A v \vec{v} \tag{5}$$

or, separated into the components (**Equations 6** and **7**):

$$a_x = -\frac{c\rho A}{2m} v v_x \tag{6}$$

$$a_y = -g - \frac{c\rho A}{2m} v v_y \tag{7}$$

These equations are solved numerically, with initially the asteroid being at a large distance from Mars, ending in the collision with the surface.

3. Results

The parameter most interesting to us in this study is the remaining kinetic energy of the asteroid in the moment of impact, as this determines how the cratering process will evolve. The ability of the Martian atmosphere to slow down the incoming body is very small due to low density of the atmosphere. Modelling shows it is insignificant for asteroid masses larger than about 100 kg. The maximal dynamic pressure for stony asteroids passing through a "standard" Martian atmosphere is shown in **Figures 2** to **6**.

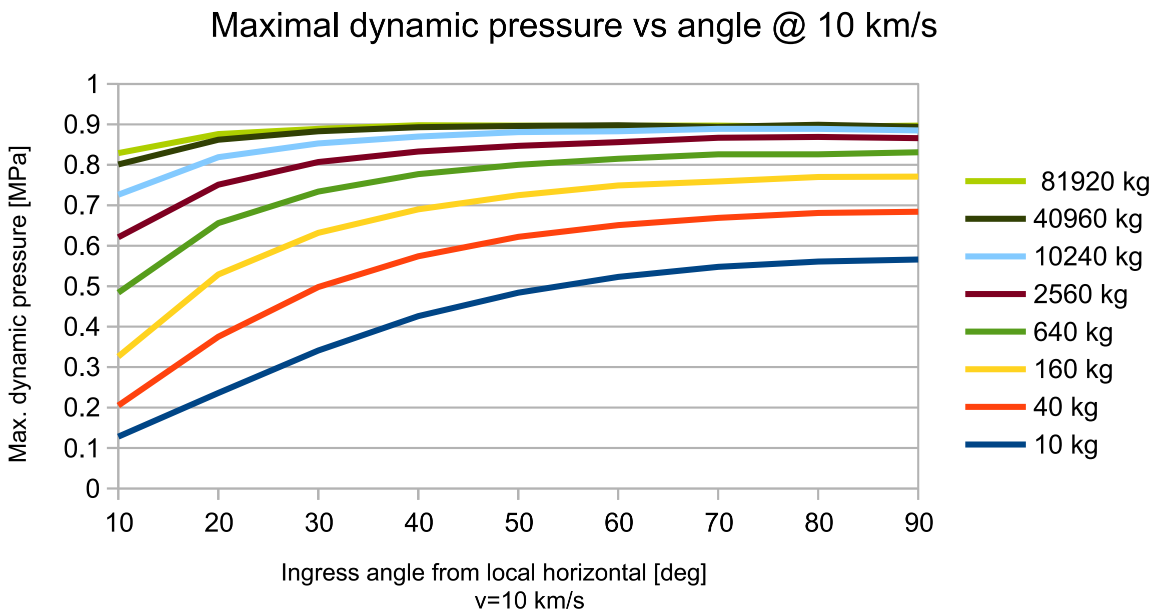

Figure 2: Maximal dynamic pressure as a function of angle of entry (measured from the local horizontal) for asteroids of varying mass and initial velocity of 10 km/s

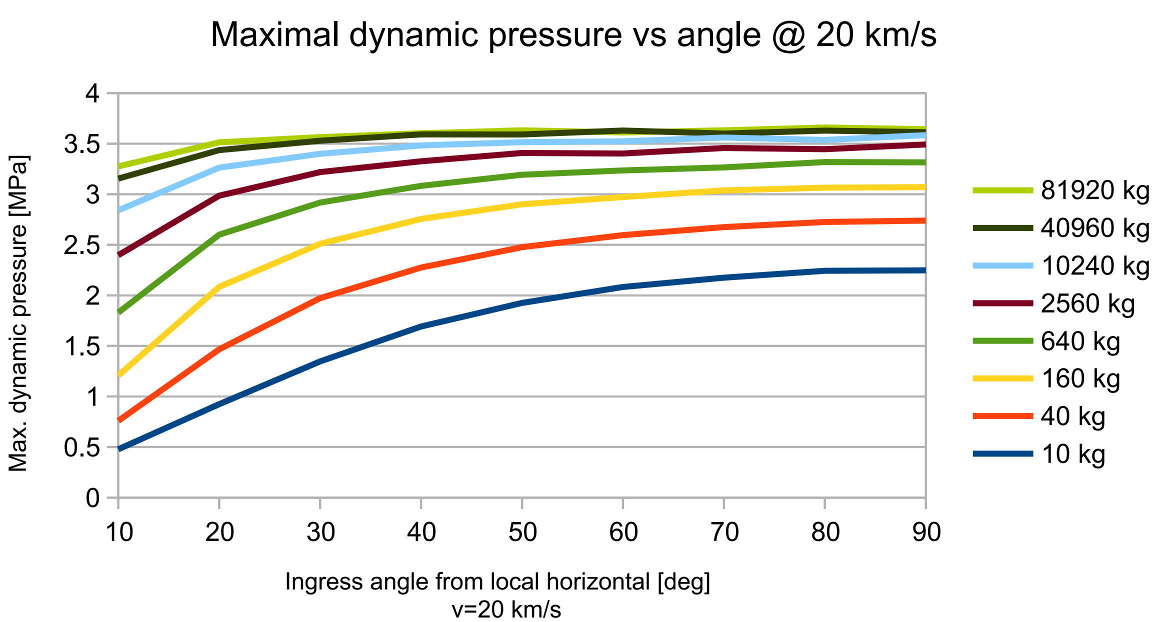

Figure 3: Maximal dynamic pressure as a function of angle of entry (measured from the local horizontal) for asteroids of varying mass and initial velocity of 20 km/s

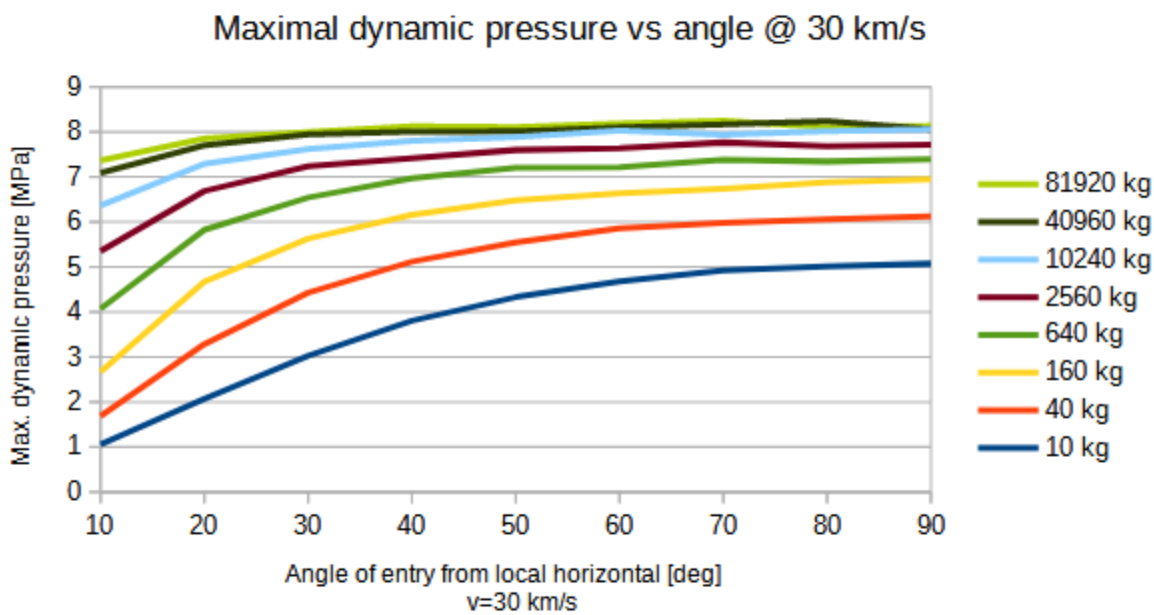

Figure 4: Maximal dynamic pressure as a function of angle of entry (measured from the local horizontal) for asteroids of varying mass and initial velocity of 30 km/s

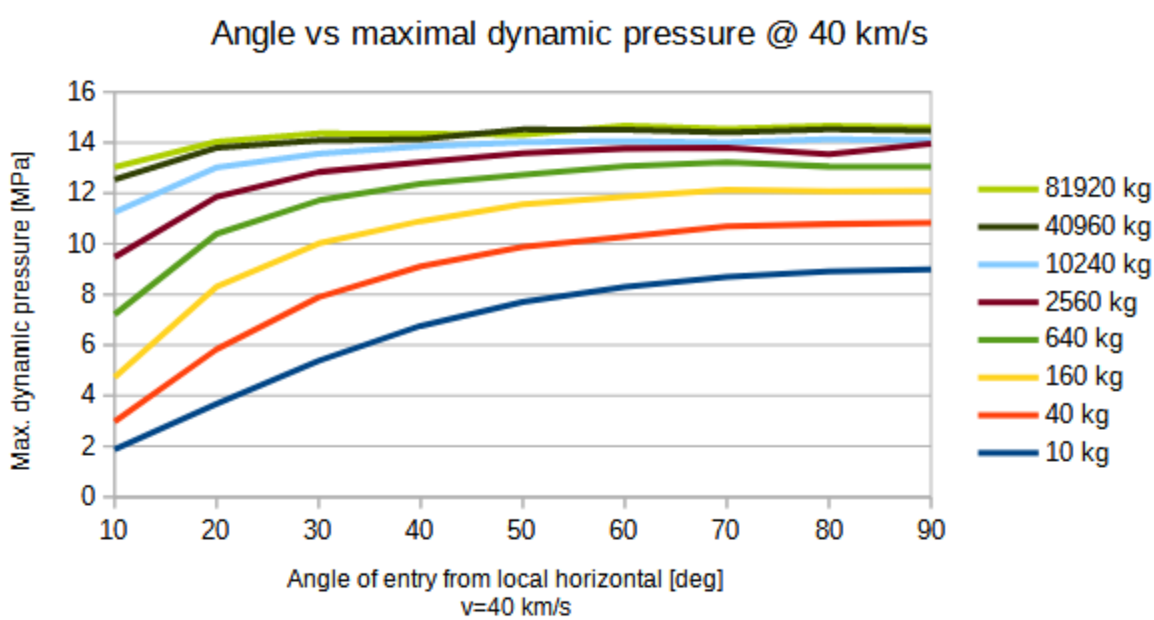

Figure 5: Maximal dynamic pressure as a function of angle of entry (measured from the local horizontal) for asteroids of varying mass and initial velocity of 40 km/s

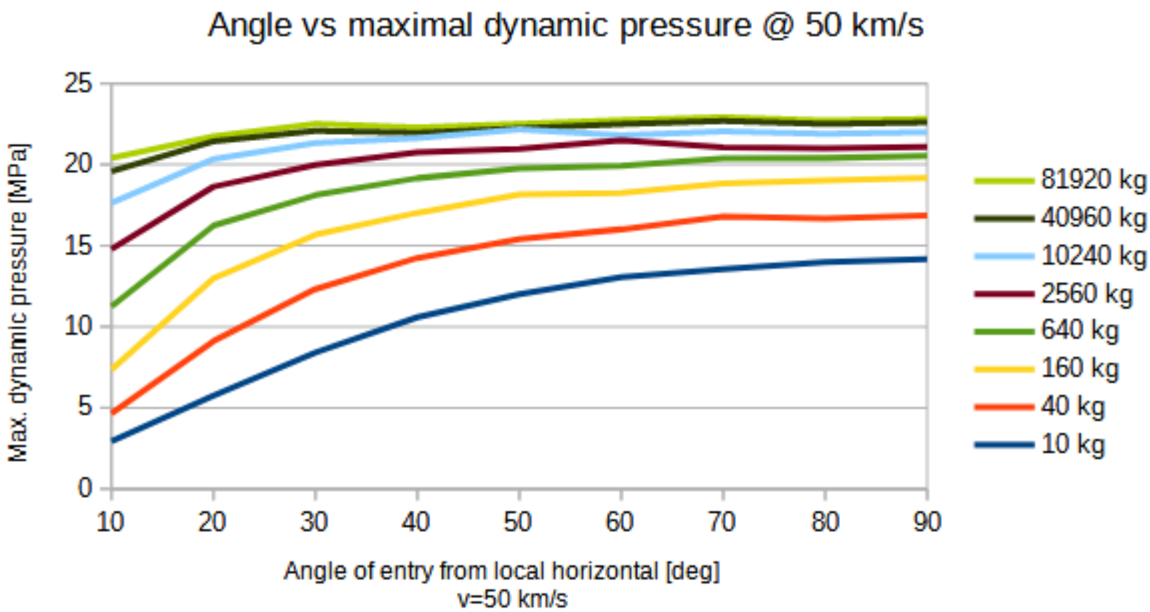

Figure 6. Maximal dynamic pressure as a function of angle of entry (measured from the local horizontal) for asteroids of varying mass and initial velocity of 50 km/s

Maximal dynamic pressure exerted on an asteroid at a given velocity increases with the mass. Also, as initial velocity (taken as a parameter) increases, so does the maximal dynamic pressure. If both velocity and mass are at fixed values, maximal dynamic pressure increases with increasing angle of entry from horizontal. The graphs on Figures 2-6 allow us to judge the maximal dynamic pressure for any combination of initial parameters. Generally, we can conclude that the maximal dynamic pressure is more influenced by the angle of entry for low mass meteorites, less for high mass ones. The maximal dynamic pressure generally increases with the initial velocity. At low velocities (~10 km/s) maximal dynamic pressure is spread in the range from 0.1 MPa to 1 MPa. At midrange velocities (30-40) maximal dynamic pressure values are distributed over the interval from 2 - 15 MPa. For large velocities in 40-50 km/s range, maximal dynamic pressure lies in 3 - 25 MPa interval.

The remaining kinetic energy in the moment of the impact is the most important factor that determines if, and how, the cratering process will evolve. The results of the model are shown on the **Figures 7** to **15**. As the remaining kinetic energy depends on three parameters, assuming a "standard" atmosphere with a constant surface pressure, different combinations of parameters are used to produce easy-to-read two-dimensional graphical representations. Obviously, the remaining kinetic energy grows with the mass and is roughly proportional to the square of the velocity, at least for more massive asteroids. The incoming angle dependence is more pronounced for less massive asteroids, as atmospheric drag influences them more than the more massive ones. Altogether, **Figures 7** to **15**. allow assessing the remaining kinetic energy at impact for any combination of these parameters.

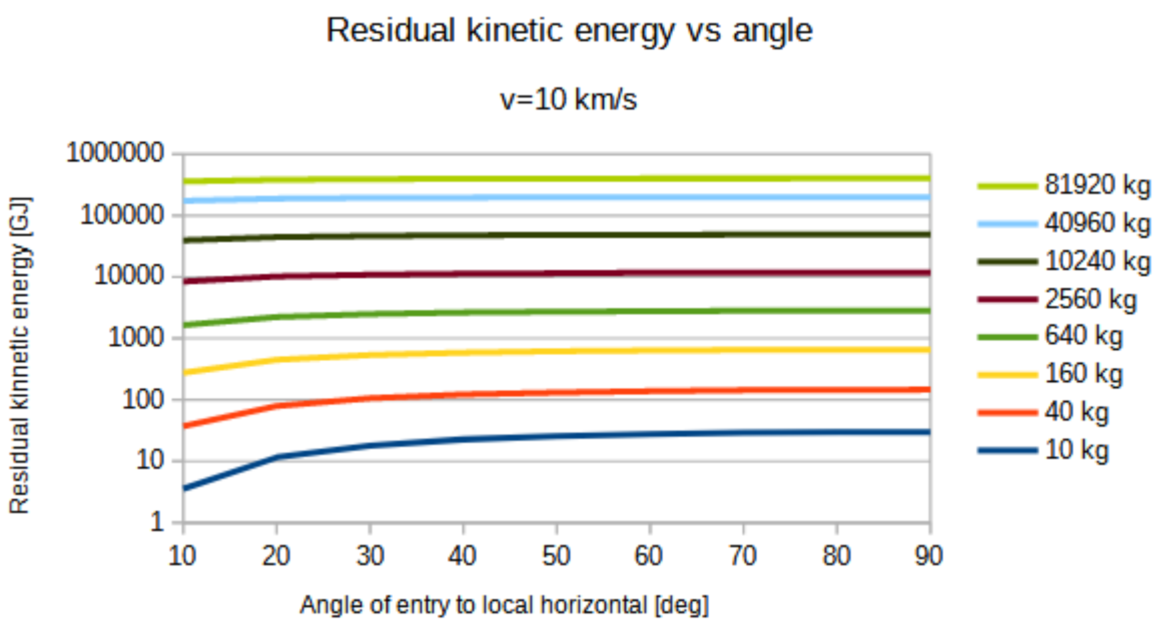

Figure 7: Dependence of residual kinetic energy on angle of entry for various asteroid masses, for initial velocity of 10 km/s.

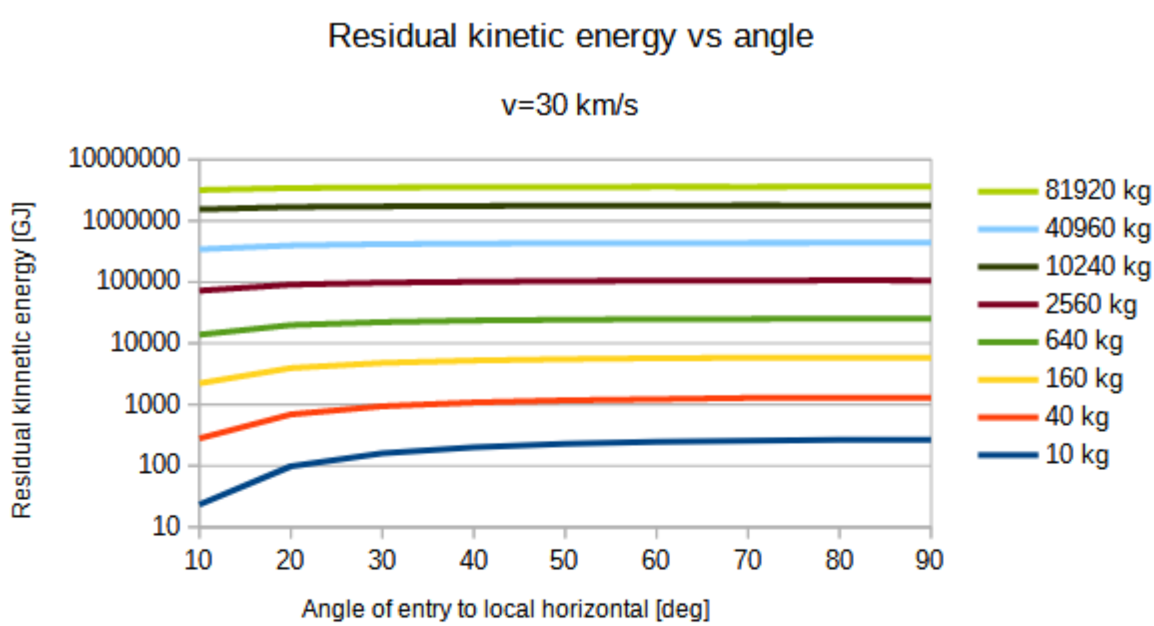

Figure 8: Dependence of residual kinetic energy on angle of entry for various asteroid masses, for initial velocity of 30 km/s

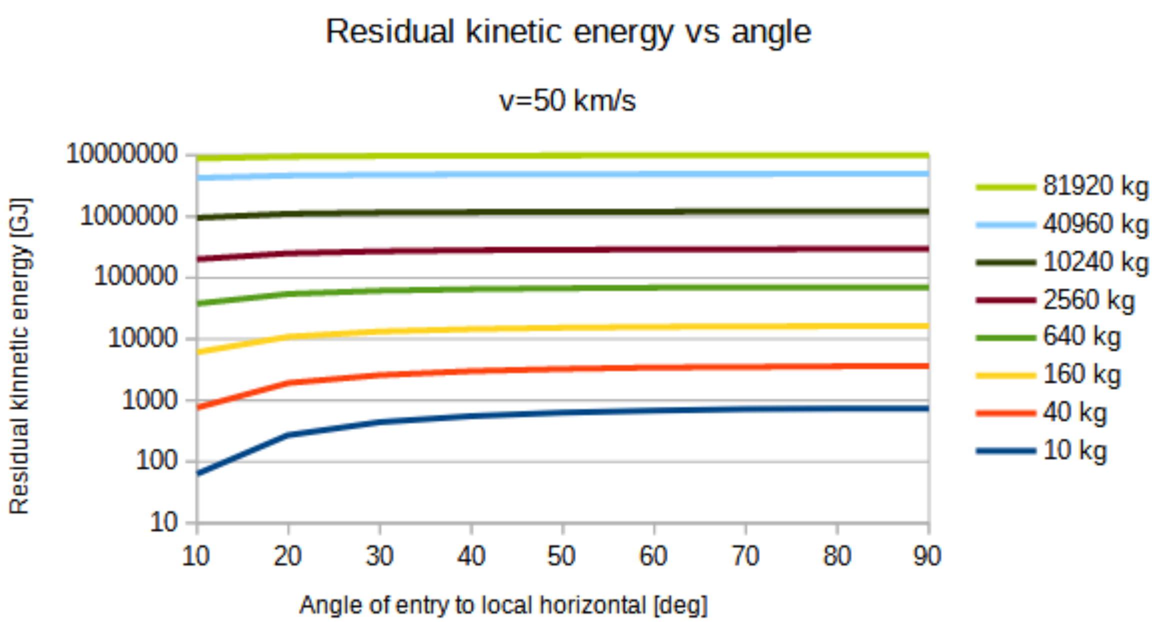

Figure 9: Dependence of residual kinetic energy on angle of entry for various asteroid masses, for initial velocity of 50 km/s

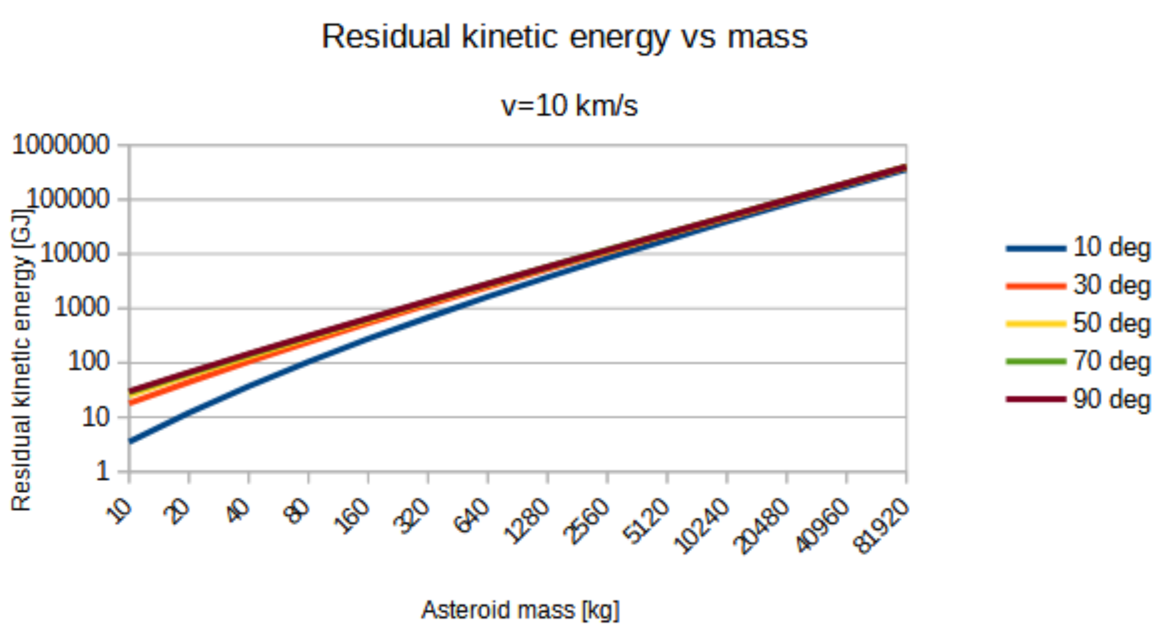

Figure 10: Residual kinetic energy as a function of the asteroid mass, at fixed velocity of 10km/s

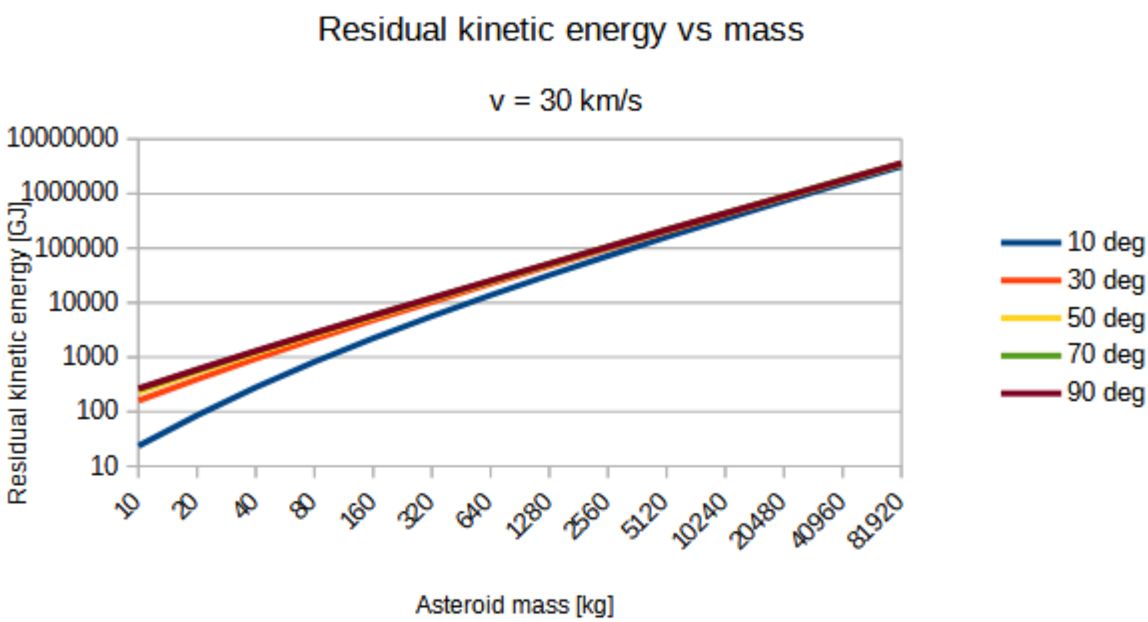

Figure 11: Residual kinetic energy as a function of the asteroid mass, at fixed velocity of 30km/s

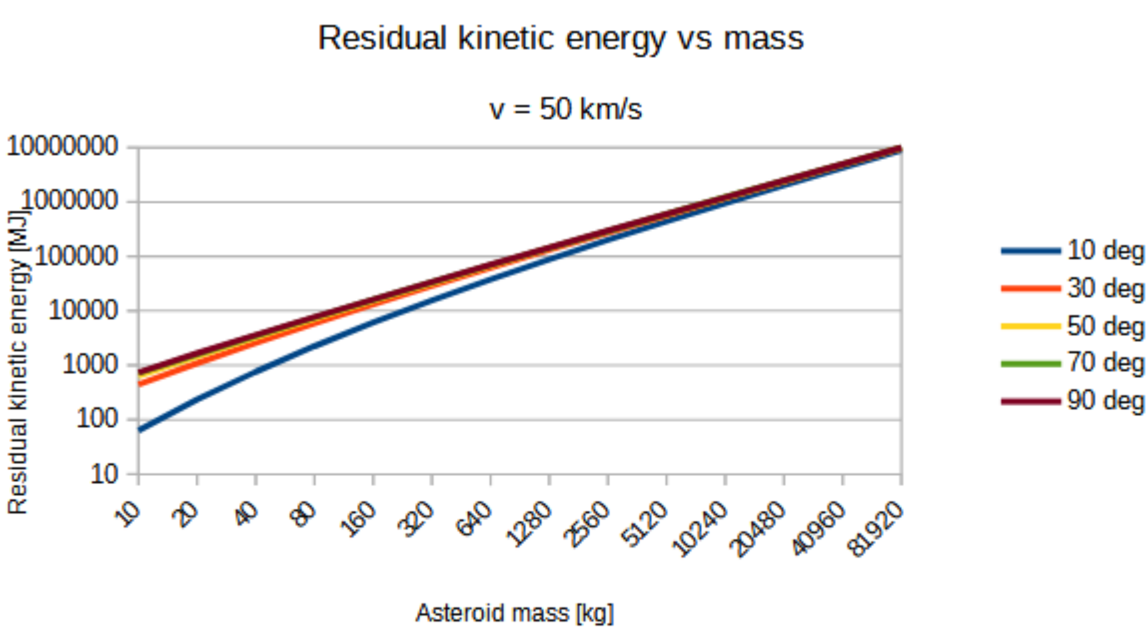

Figure 12. Residual kinetic energy as a function of the asteroid mass, at fixed velocity of 50km/s

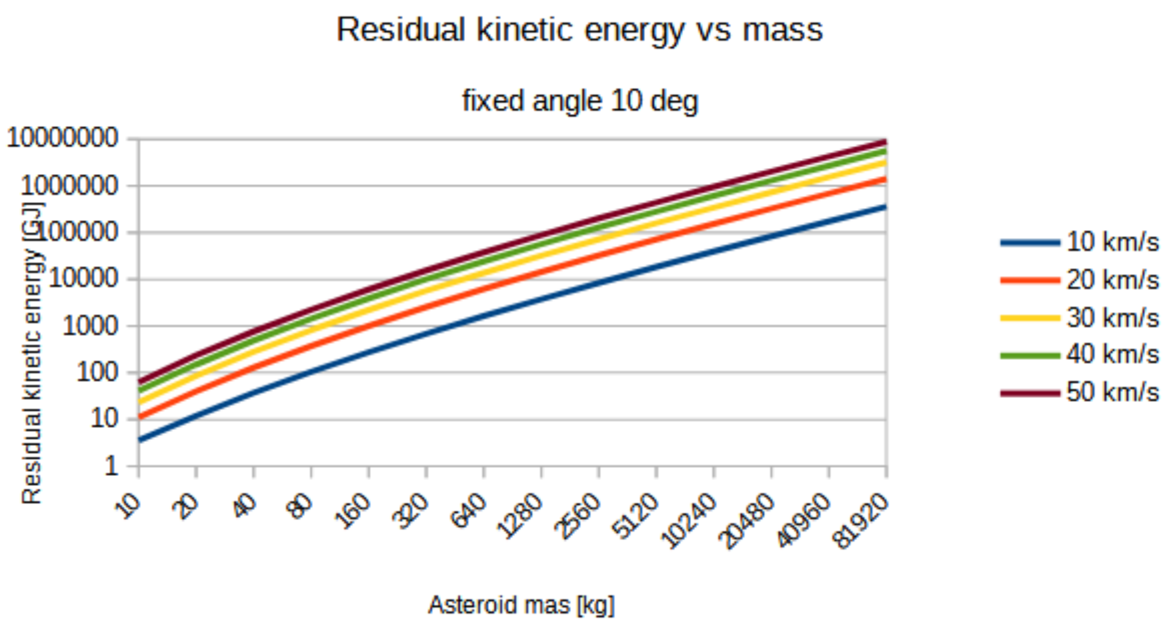

Figure 13: Residual kinetic energy as a function of the asteroid mass, at fixed angle of entry of 10 deg

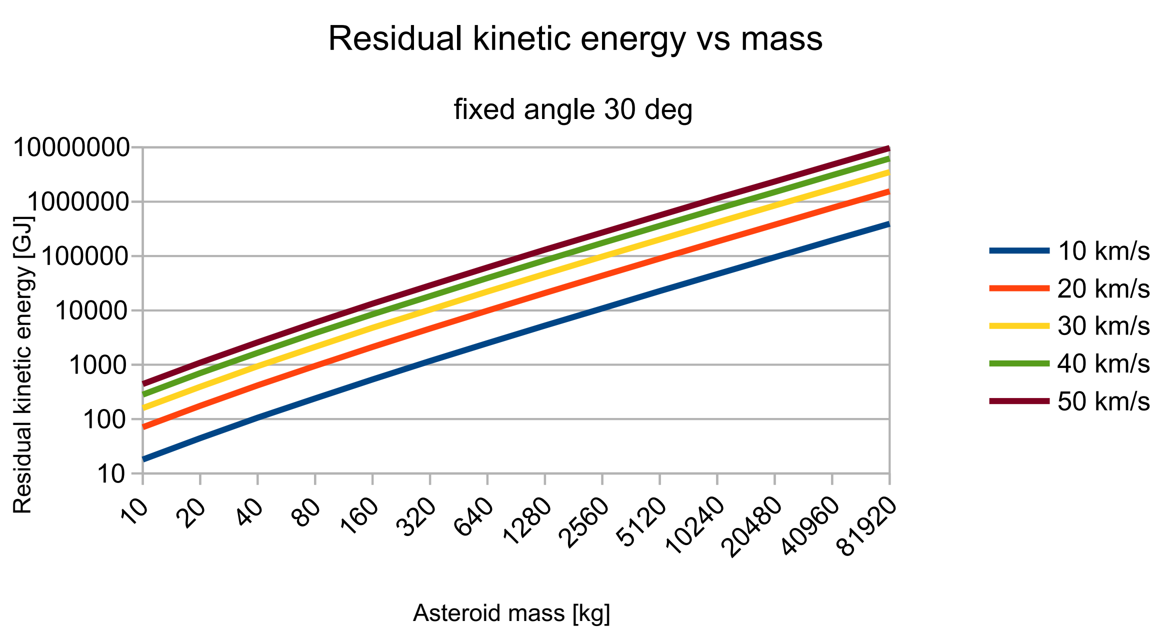

Figure 14: Residual kinetic energy as a function of the asteroid mass, at fixed angle of entry of 30 deg

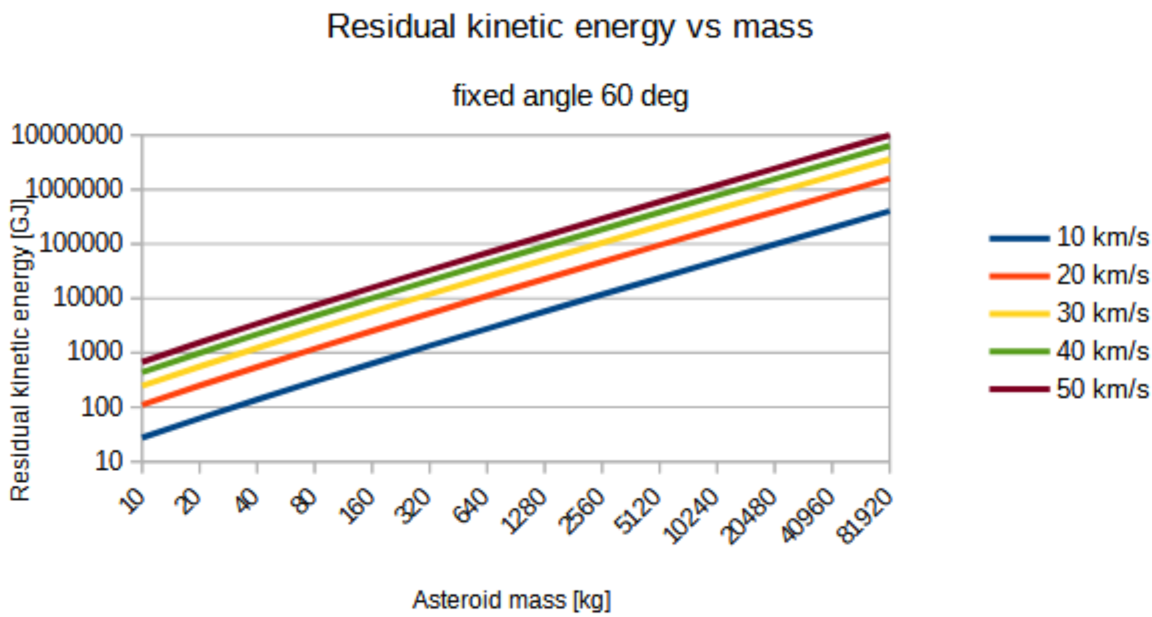

Figure 15: Residual kinetic energy as a function of the asteroid mass, at fixed angle of entry of 60 deg

4. Discussion

Dynamic pressure can be used to distinguish between bodies that reach the ground intact (assuming no thermal ablation) and those that break up due to aerodynamic forces acting on the incoming body. Those reaching the ground are considered impactors and are crater forming candidates. Incoming bodies that do break up in the atmosphere won't be treated as potential impactors. Rather low dynamic pressures are due to the rare Martian atmosphere, so we assume that the breakup happens mainly to bodies composed of loosely bound material. We did not treat such cases in our study.

In-flight breakup of the incoming asteroid due to forces originating from interaction with the planet's atmosphere happens when dynamic pressure becomes larger than asteroid's critical or break-up pressure. Calculations show that for the most part, velocity at the zero height is only slightly reduced compared to the in-flight velocity of the asteroid. This, in turn, means that in most cases, neither terminal velocity nor the maximal dynamic pressure is reached before the impact. Therefore, the rarity of Martian atmosphere along with presumed compactness of stony asteroids suggest relatively small dynamic pressure to critical pressure ratio, reducing the probability of a breakup.

The results of Martian impacts are directly linked to the Martian geology and stratigraphy. It could be compared with the Earth's geology, where the oldest geological units, eons, are time periods characterised with the planet forming and developing of the main structures of core, asthenosphere, and lithosphere. Most impacts on the Earth, as well as other terrestrial planets, happened during the first eon called Hadean (4-5-4.0 Ga), when the Earth's structure differentiated and the Moon had formed after collision with another planet (**Portegies Zwart, 2009**; **Kaib & Quinn, 2008**; **Greaves, 2005**). The Hadean had been followed by the Archean (3.9-2.5 Ga), the Proterozoic (2.4-0.55 Ga) and the Phanerozoic (0.54 Ga-rec.). The Martian geological history is also divided into chronostratigraphic units of lower ranks – periods. They are pre-Noachian (4.5-4.1 Ga), Noachian (4.0-3.8 Ga), Hesperian (3.7-3.0 Ga) and Amazonian (2.9 Ga-rec.), defined by studies of impact crater density on planet surface (**Tanaka, 1986**; **Caplinger, 2007**).

All impacts on the Mars are greatly influenced by low surface gravity (38 % of the Earth's) and surface lithology. The planet diameter is 6790 km (half of the Earth's) and general density is 3.9 g/cm^3 (primary silicate with small metal core). The result of impact is mostly determined with interplanetary object's speed and the lithology of the Martian surface (**Figure 16**) at the impact site.

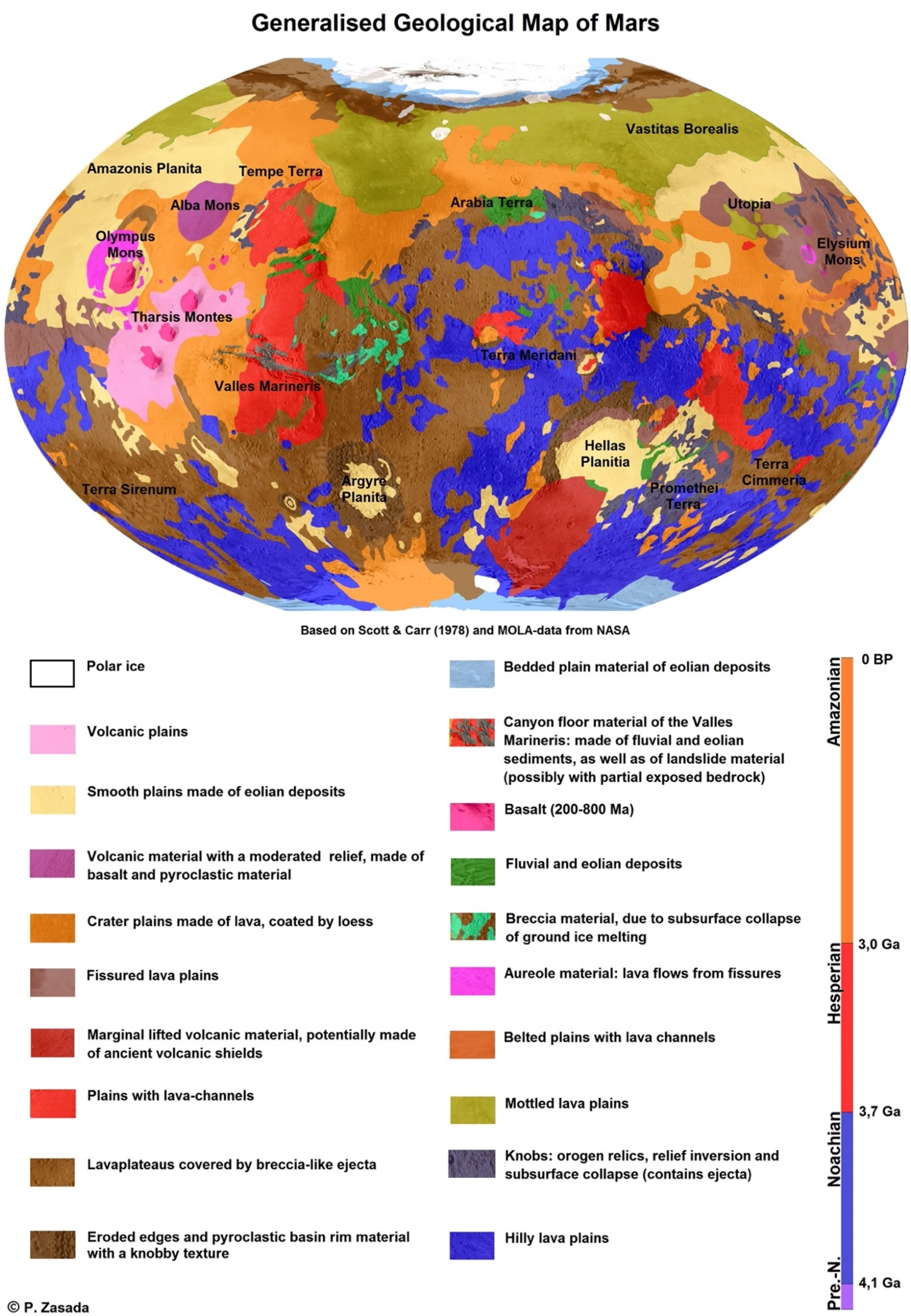

Figure 16: Generalised Geological Map of Mars, 1:140.000.000 (**Zasada, 2013**)

The size of craters, regarding surface lithology, is directly linked to the rock density on the bottom of the crater. The magmatic rocks, especially uplifted intrusive rocks, will be more resistant impacts than sedimentary ones. Weathering decreases the resistance to impacts and the role of Martian soil, regolith, especially one of aeolian origin and can diminish the consequences of the impact. Generally (***), the Martian craters are shallower and smoother than the Lunar ones, due to significantly stronger erosional and depositional geological history. However, the Martian impacts are also result of hypervelocity impacts and are more morphologically complex when larger (***). They can be classified as: (a) simple craters with the diameter <7 km; (b) more complex craters (>7 km), having central peak(s) and (c) extremely large multi ring basins (>100 km) where central peak is replaced with concentric rings of hills.

5. Conclusions

Dynamic pressure was found to be insufficient to affect breakup of stony asteroids, meaning that they will reach the surface in one piece. Rather low dynamic pressures are a natural consequence of the rarity of the Martian atmosphere.

The surface effects of Martian impacts are linked to the Martian geology and stratigraphy. Most impacts on the Earth and other terrestrial planets happened during the Hadean (4-5-4.0 Ga), when the Earth differentiated and the Moon had formed. The Martian geological history is also divided into chronostratigraphic units of lower ranks – periods. They are pre-Noachian (4.5-4.1 Ga), Noachian (4.0-3.8 Ga), Hesperian (3.7-3.0 Ga) and Amazonian (2.9 Ga-rec.), based on studies of impact crater density on planet surface.

Impacts on the Mars are shaped by low surface gravity (38 % of the Earth's) and Martian surface lithology. The planet diameter is half of the Earth's and mean density is much lower, roughly 3.9 g/cm^3. The final result of an impact is determined by the impactor's size, speed and impact angle, combined with the lithology of the Martian surface at the impact site.

The size of craters is determined by the rock density on the bottom of the crater. The magmatic rocks, especially uplifted intrusive rocks, will be more resistant to impacts than sedimentary ones. Martian regolith, especially one of aeolian origin can diminish the consequences of the impact. Generally, Martian craters are shallower and smoother than the Lunar ones, due to significantly stronger erosional and depositional geological history. However, they can be clasified in the same way as lunar ones, namely: simple craters with the diameter smaller than about 7 km, more complex larger craters, having central peak(s) and extremely large multi ring basins with sizes greater than about 100 km.

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Sažetak

Udari malih asteroida i nastanak kratera na Marsu

Istraživane su posljedice udara malog asteroida (manje od 100 T mase) u površinu Marsa. Ustanovljeno je da ni atmosfersko kočenje ni maksimalni dinamički tlak ne utječu bitno na padajuće tijelo. Drugim riječima, asteroid ostaje cjelovit sve do samog udara u tlo. Veličina nastalog kratera ovisi o kinetičkoj energiji asteroida i litološkim svojstvima marsove površine i plitke kore, kao i o kasnijoj atmosferskoj eroziji.

Ključne riječi: Mars, krateri na Marsu, let meteorita

Author’s contribution

I.S. analysed the results and prepared graphs. Ž.A. made the numerical flight model and carried out the calculations. T.M. and U.B. made the context of Martian geology on impacts and described impacts origins in the Solar system.