FATE OF SOLID EJECTA AFTER THE CHICXULUB IMPACT. N. Artemieva[1] and J. Morgan[2], [1]Planetary Science Institute, Tucson AZ, artemeva@psi.edu, [2]Imperial College, London UK, j.v.morgan@imperial.ac.uk.

Introduction: The cause of the K-Pg mass extinction remains a matter of some debate, but the environmental effects of climatically-active gases released from sedimentary rocks at the Chicxulub impact site is still one of the widely-favored kill mechanisms [1-3]. Recently, using new constraints on the Chicxulub impact angle and target composition, we estimate that 325 ± 130 Gt of sulfur and 425 ± 160 Gt CO_2 were ejected and produced severe changes to the global climate [4]. Whereas these results are comparable to previous estimates [5-6], we also find that a much larger mass, ~12,000 Gt, of high-velocity ejecta is composed of solid sedimentary rock, i.e., shock pressures are not high enough to cause complete degassing.

Atmospheric heating during ejecta re-entry has been suggested as a source of global fires and mass extinction [7]. Later, numerical models [8-10] revealed that the radiation flux to the Earth's surface is reduced by substantial screening [8], and that local fires could only occur in certain directions at proximal to intermediate distances from the impact site[10]. However, substantial heating of re-entering particles certainly takes place and may cause their partial or total ablation.

Methods: We use the multi-phase hydrocode SOVA [11], which is a 3D Eulerian code that models multidimensional, multimaterial, large deformation, strong shock wave physics. The code has the capability to model so-called dusty flows – the interaction of solid or molten particles with gas. In this method, each fragment is characterized by its individual parameters (mass, density, position, and velocity) and is subjected to gravity and drag. Additionally, the particles exchange heat with the atmosphere via convection and conduction.

Results: First we consider how ejecta heat atmospheric gases during re-entry and its dependence on the particle size, velocity, and mass flux. Then we estimate the time interval required for total decomposition of calcite particles and for melting of silicate fragments. Finally, we estimate degassing of solid high-velocity ejecta and its contribution to the climate-active gases inventory after the Chicxulub impact.

Influence of re-entry velocity and size. Fig. 1 shows temperature of the atmospheric gas surrounding particles of different sizes during their re-entry at 3 km/s (the minimal velocity of the solid ejecta to reach North American, NA, sites). For each run we have particles of only one size. Particles of all sizes are heated to 2000 K and stay at temperature > 1000 K for at least 20 seconds. At higher velocities temperatures are higher, but the duration of the heat pulse is approximately the same. If particles of various sizes enter the atmosphere simultaneously, then the smallest, 0.1-mm-diameter, particles stay at elevated temperatures for a few minutes as they are entrained within flowing gases heated by larger particles.

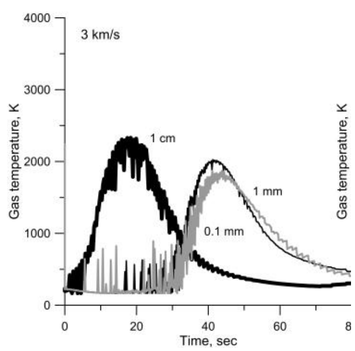

Fig. 1. Gas temperature during the re-entry of 0.1 mm-1cm particles at 3 km/s. The total mass is 100 kg/m^2, i.e., ejecta deposits are 4-cm-thick. All particles arrive at the top of the upper atmosphere simultaneously.

Influence of the mass flux and the total re-entering mass. In real impacts ejecta arrive at the upper atmosphere over an extended time period (10 -1000 s) as materials are ejected at slightly different velocities and angles [9]. In Fig. 2 temperature distributions around 1-mm particles are shown for a mass flux of 1 kg/m^2/s with particles entering the upper atmosphere over 100 s (typical time interval for NA sites).

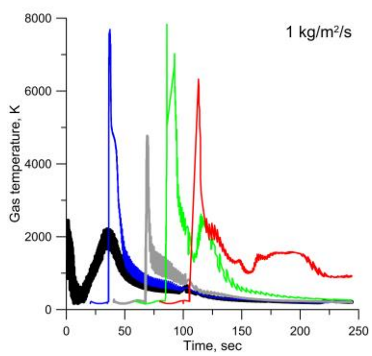

Fig. 2. Temperature around 5 representative 1-mm-sized particles that are 20 s apart within ejecta arriving over 100 s. Compared to Fig. 1, the maximum temperatures are much higher (up to 10000 K, but the total duration is shorter (~10 s). Some particles are entrained within a rising flow of hot gases and are subjected to the second pulse of heating (see red and green curves and also Fig. 3).

Total mass of ejecta per sq.m. has only slight influence on the heat pulse in the range typical for NA sites (50-200 kg/m^2, or 2-8-cm-thich deposits).

Ejecta curtain evolution. Then we model ejecta re-entry and atmospheric heating using ejecta scaling and realistic size-frequency distributions (SFDs). Particles re-enter the atmosphere at an altitude of 150 km. Qualitative illustration of the process is shown in Fig. 3. Smallest particles (0.1-1mm) are not deposited ballistically, instead, they are entrained within a turbulent flow of hot air.

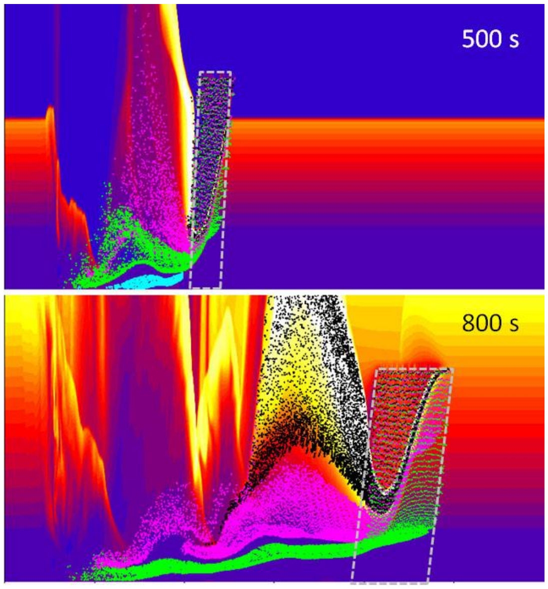

Fig. 3. Atmospheric temperature during ejecta re-entry after the Chicxulub impact. Each snapshot has dimensions 6000 km * 200 km. Particles are colored according to their size: 10 cm – cyan; 1cm – green; 1 mm – magenta; 0.1 mm – black. Temperature colors change from 0 (blue) to 1000 (red), 2000 (yellow), and 3000 (white). The ejecta curtain moves from left to right; dashed lines delineate the ballistic curtain.

Decomposition and melting of particles at elevated temperature. In addition with entry models, we solve the heat transfer equation for a spherical particle, surrounded by its own vapor (1150 K for calcite and 1940 K for silicate). To include the phase transition we use an artificial increase of heat capacity if material temperature is between solidus and liquidus. In both cases the time interval of total decomposition/melting is ~1 sec. To use these results for larger/smaller particles, the time interval should be multiplied by C^2, where C is spatial scale coefficient. For example, a 1-cm particle (C=10) is totally decomposed within 100 seconds.

Preliminary estimates for the Chicxulub impact. In [4] we found that the total mass of high-velocity (> 1 km/s) solid ejecta from the Chicxulub is 4.6 times larger than the projectile mass M_{pr}. However, this ratio decreases quickly with increasing ejection velocity; it's about 1.2 for velocities > 2 km/s, and only 0.4 for velocities > 3 km/s.

Our preliminary models show that re-entering velocities of 1 km/s are not high enough to cause substantial decomposition, whereas velocities of 2-3 km/s result in heating above > 1150 K. To be conservative, we assume that the total mass of these ejecta is approximately equal to the projectile mass. The next question is the SFD of these ejecta as only particles <1 cm could be heated through within tens of seconds. The SFD problem is a major uncertainty in ejecta modeling: observations are limited to larger sizes whereas experimental data cannot be directly extrapolated to natural events. However, in the case of porous water-saturated limestone from the Chicxulub impact site, we hypothesize that materials subjected to shock pressures > 6-10 GPa (vaporization of water) are eventually fragmented into very small particles (as it happens in experiments with water-saturated rocks, e.g., [12]). All ejecta with V > 2 km/s have been subjected to pressures > 6 GPa.

Discussion: Whereas the mass of CO_2 released during the impact is ~400 Gt, our preliminary estimates suggest that at least twice that mass could be additionally released into the atmosphere during ejecta re-entry, although this may be reducd by back reactions. In contrast to immediate decomposition near the impact site these gases are distributed globally.

Presence of solid sedimentary rocks in Chicxulub ejecta is consistent with the observation of fine-grained shocked and unshocked carbonate and dolomite clasts in the upper layer of the K-Pg boundary at the Demerara Rise, where they are coincident with shocked tectosilicates [13]. The authors interpret some of the morphologic features (fluidal-shaped µm-sized pores) in these clasts as evidence of their formation within the high-temperature impact plume. We propose an alternative explanation, that these high-temperature features may also have been formed when the clasts were heated during atmospheric re-entry. Recently a 80-cm-thick micrite layer has been recovered during the Chicxulub drilling project [14] and, seems, it could be a global feature. Possibly, this micritic layer is formed from heating of solid calcite during ejecta re-entry.

Acknowledgements. This study is supported by Exobiology NASA grant NNX16AI30G

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