DISTAL EJECTA FROM THE CHICXULUB – NUMERICAL MODEL. N. Artemieva[1,2] and J. Morgan[3], [1]Institute for Dynamics of Geospheres, Moscow 119334, Russia. [2]Planetary Science Institute, Tucson 85719, AZ, artemeva@psi.edu. [3]Imperial College London, UK, j.morgan@imperial.ac.uk.

Introduction. Shocked quartz grains found at K-P boundary [1] soon after the first publication of its extra-terrestrial origin [2] provided the strongest confirmation of the hypothesis. Six years later, the parent crater Chicxulub was found on the shore of the Mexico Gulf [3]. Although we now have good constraints on the size of this impact and chemistry of the target rocks, estimates of its environmental consequences and possible mechanisms of mass extinction are still debated. We started this project with the aim to reconstruct possible impact scenarios, and to estimate the total amount of materials ejected into the atmosphere (as well as their velocities and physical states) using three-dimensional numerical modeling and comparison of the results with available observations. In particular, we are interested in ejecta distribution, as previous studies of the K–P ejecta [4-5] suggested an intriguing asymmetry which may be directly connected with impact obliquity and direction [6-9].

Numerical methods and initial conditions. We model the impact and high-velocity impact ejecta motion using 3D hydrocode SOVA [10] complemented by the ANEOS equation of state for geological materials [11]**.** We use a tracer particle technique to reconstruct dynamic (trajectories, velocities), thermodynamic (pressure, temperature) and disruption (strain, strain rate) histories in any part of the flow. All materials above the altitude of 10 km, subjected to tension are disrupted into particles with a size-frequency distribution defined by maximum shock compression [12]. The motion of these fragments in the post-impact plume is described in the frame of two-phase hydrodynamics.

We use a simplified description of the Chicxulub target similar to previous models [14-15], with a 3-km-thick layer of sediments (calcite EOS), a 30-km-thick crystalline basement (granite EOS), and mantle (dunite EOS). In this study we do not scale projectile size with impact angle and use the value of 14 km, justified in previous numerical models for a vertical impact by thorough comparison with available geological data. Impact angles are 45º and 30º to horizon.

Ejecta - velocities and mass. We have found that early ejecta are really asymmetric but surprisingly ejecta do not contain any materials from the crystalline basement. Maximum velocity of shocked quartz rarely exceeds 2 km/s. The high-velocity ejecta are exclusively from the uppermost layers of the target [9,17], while the quartz-bearing crystalline basement at the Chicxulub impact site is at > 3 km depth. The popular idea of particles' acceleration within the plume [18] is not confirmed in our simulations. On the contrary, tracers' history reveals standard deceleration in the Earth's gravity field.

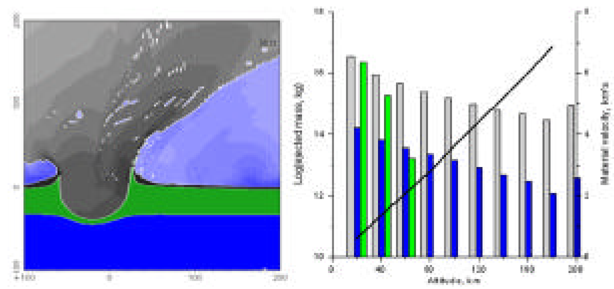

Fig. 1. On the left - cross-section of the Chicxulub post-impact plume 35 seconds after the 45° impact: gray color shows sediments, blue – atmosphere and mantle, green – crystalline basement. On the right – mass (bars and left axis) and velocity (solid line and right axis) distribution of the plume materials across the altitude.

Ten seconds after the impact all materials (shocked and molten quartz, solid sediments) within the lower part of the plume move at similarly low velocities, while the upper portion of the plume, containing vaporized sedimentary rocks and projectile, reaches the altitude of 200 km with escape velocities.

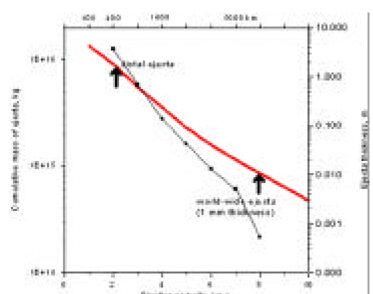

Fig. 2. Cumulative mass-velocity distribution of ejected materials (red line) and estimated thickness of deposits (thin black line)

35 seconds after the impact velocity distribution in the plume is linear (see Fig.1) in agreement with the standard solution for gas expansion. All granite is below the altitude of 70 km with maximum velocity of 2.5 km/s. While the total amount and estimated thickness of distal and worldwide ejecta is comparable with observations (a few cm at intermediate distances of 2000-4000 km, and 1-3 mm worldwide – see Fig.2) the ejecta do not contain any shocked quartz. Also, maximum distances reached by the crystalline rocks (including molten rocks) on ballistic trajectories never exceed 700 km. Thus, standard hydrocode modeling failed to reproduce the worldwide Chicxulub ejecta

and the well-known dual impact layer (thick lower claystone sharply separated from a thinner upper layer with Ir-anomaly) in North America.

Possible reasons of ejecta low velocity: Errors in the SOVA code may be eliminated: the hydrocode was thoroughly tested; mass, momentum and energy conservations are under strict control during the runs; the same code has produced much more high-velocity ejecta than any other hydrocode used in impact cratering. The problem with EOS is more serious: ANEOS tends to underestimate energy of materials subjected to phase transition. However, comparison with updated quartz EOS shows very little difference in expansion velocities. Possible back reactions in calcite are not taken into account in this model, but they cannot influence the shocked quartz expansion as these materials are substantially separated in the plume.

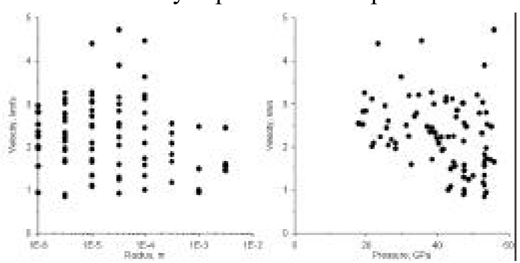

Fig.3 Escaping particles: velocities versus size on the left (size distribution is not continuous in the model), velocities versus maximum compression on the right.

Other reasons include incorrect (by an order of magnitude) estimate of the Chicxulub diameter or substantially different target structure (such as much thinner sediments or quartz-buried dykes within the sediments). Both are unlikely as the target rocks are well known through drilling [e.g. 3] and the Chicxulub size – through seismic study and geophysics [19-21]. Thus, we conclude that the mechanism of ejecta dispersion and distribution is different from standard ballistics or/and plume acceleration.

Non-ballistic transport. While standard hydrodynamics describe a continuum media, i.e. all materials ejected at the same place and at the same time move along the same trajectories, the actual situation may be different: vaporized rocks expand separately from solid fragments, large boulders follow ballistic trajectories, while small ones and molten droplets may be involved into the plume by turbulence. The results of our late-stage modeling (up to 15 minutes) show that some amount of the particles from the crystalline basement has eventually reached the boundaries of computational box (located at the distance of 1000 km from the impact site and at the altitude of 500 km) and has escaped it. The size of these particles ranges between 1 μm (lower limit in modeled SFD) to 3 mm. Shock compression is from 20 GPa to 55 GPa (melting point), i.e. these particles may have PDFs. As particles have been subjected to turbulent mixing, we do not see any correlations between velocity and shock pressures, or velocity and size (Fig. 3). Also spatial distribution is more symmetric than the initial one.

Discussion - how much shocked quartz we need for the global layer? The total volume of microkrystites in K-P layer, assuming global coverage, is about 850 km^3 [22]. At the same time, the total volume of shocked quartz in this layer is in the range of 0.04 – 0.14 km^3 (see Table 1, based on shocked quartz measurements [23]). Our model produces about 0.05 km^3 of shocked quartz at the altitudes above 500 km, which may be globally dispersed. This value is at the minimum limit of our estimates (Table 1). Symmetric distribution of shocked quartz, obtained in [23], may be the consequence of ejecta re-distribution in the vapor plume, not the result of a near-vertical impact. Another 1.2 km^3 are at lower altitudes (<200 km) but at the distances of 1000 km from the impact site (in downrange direction). Unfortunately, this value is two orders of magnitude less than in the North America dual impact layer and the problem remains unresolved.

Table 1. Estimated amount of shocked quartz

Distance, 10^3 km	Mean size, μm	Nos/cm^2	Volume, km^3
<3	60-80	800-1100	0.027-0.088
3 – 6	45-55	300-400	0.011-0.028
> 6	35-45	70-130	0.006-0.025
Total			**0.044-0.141**

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