EJECTA DISPERSAL AND INFRA-RED PULSE GENERATION BY THE CHICXULUB IMPACT.

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Introduction: The scientific community has long been aware that the fossil record is punctuated by five mass extinctions. However there is still considerable debate regarding the timing and causes of all these events. No mass extinction is more controversial than the end-Cretaceous episode.

Since the seminal paper by Alvarez et al. [1], a huge amount of research has been conducted, world-wide, gathering data relating to meteorite impacts and their effect on the biosphere. Recently, crucial work has been carried out on the Chicxulub structure [2], allowing the quantification of important impact parameters, such as the kinetic energy of the meteorite and the mass of material ejected from the crater. This information allows the environmental perturbations, caused by the impact, to be determined more accurately.

One prominent effect is the heating of the surface and atmosphere, caused by the re-entry of ejecta [3]. Material is evacuated from the crater, launched on ballistic trajectories and re-enters the Earth's atmosphere at velocities up to 11km/s (escape velocity). The small particles of ejecta accelerated to these high speeds (mostly sub-mm) are decelerated in the middle atmosphere by molecular drag [4]. As they rapidly slow to terminal velocity (close to 0km/s), the vast majority of their kinetic energy is transformed to heat, enough to cause the larger particles to melt. The ejecta cools, emitting radiation in the near and mid infra-red range. Half of this energy is directed downwards and although water vapour and carbon dioxide absorb certain wavelengths, around 30% of this energy can potentially reach the ground. However, the spatial and temporal distribution of the re-entering ejecta and hence of the infra-red (IR) pulse, is not globally uniform. This distribution must be quantified if the relative environmental effects, in contrasting geographical regions, are to be ascertained.

Modelling of ejecta: The ejecta was initially modelled as an expanding hemisphere of material, originating from a point on the surface, at the centre of Chicxulub. The velocity increases linearly from 0km/s at the centre to 10km/s at the edge [3]. The hemisphere was divided into ≈ 70000 elements and standard ballistic and spherical trigonometric equations were used to calculate the travel time and arrival location of each. The lowest 0.55 rad. were ignored for the purposes of this calculation, as little material is ejected at such low angles. It was assumed that the Earth was spherical and rotating. The Earth's surface was then divided into 0.1rad. by 0.1rad quadrants and all elements landing within a certain quadrant collated.

These elements do not represent equal masses of material, so three scaling relationships were utilized to describe the relationship between mass (M), velocity (v) and take-off angle (a).

$$M \,\alpha\, \cos(a) \qquad (1)$$

$$M \,\alpha\, v^{-2.85} \qquad a \le 0.775 \text{ rad} \qquad (2)$$

$$M \,\alpha\, v^2(1-v^2/19000^2)^8 \qquad a \ge 0.800 \text{ rad} \qquad (3)$$

Equation (1) is simply a function of the hemisphere geometry. (2) represents the ejecta curtain of solid and melted material exiting the crater at angles of 0.55 rad to 0.775 rad [5]. The power law relationship is derived from a model of crater ejecta constructed using dimensional analysis [6]. Equation (3) characterizes the high angle vapour plume, comprising vaporized target rocks, volatiles released from the target rocks, the partially vaporized impactor and entrained solids and melts. This scaling relationship [7] assumes a maximum vapour plume speed of 19km/s and $c_p/c_v = 4/3$.

The total mass of the ejecta was taken to be 10^{17}kg (40000km^3). This was based on the volume of the excavation cavity [2] and gravity anomaly data [8], using a density contrast of 270kgm^{-3} between the mean target rock and the infilling rock. The mass of the vapour plume was estimated as $4 \cdot 10^{15}$kg, based on field observations [9,10].

Using these values and relationships it is possible to calculate the total kinetic energy of ejecta re-entering the atmosphere over a given area, the thickness of the layer it will produce when it lands (assuming uniform deposition) and also the power of the IR pulse over time.

By applying the following equation [3] the maximum diameter of a spherical shocked quartz grain, that survives re-entry without being annealed, can also be determined.

$$T^4 = (\delta \cdot \rho_m \cdot \sin(a) \cdot v^3)/(9 \cdot e \cdot C_d \cdot \sigma \cdot H) \qquad (4)$$

Where δ, ρ_m, C_d, σ and H are spherule radius, spherule density, molecular drag coefficient, Stefan-Boltzmann constant and the atmospheric scale height respectively. T is the maximum temperature reached by a grain on re-entry. For this calculation it was given a value of 1400K, the annealing temperature of quartz [11].

Numerous K/T boundary deposits have been described in the literature as featuring shocked quartz grains [12,13]. The maximum sizes predicted by this model are in good agreement with those observed in the field. At distances exceeding 11000km, diameters under 0.20mm are anticipated and these values increase to 0.80mm at 3000km, close to the actual measurements recorded in the mid-west United States [12]. At locations proximal to Chicxulub the calculated diameters depart from the observed values, suggesting a flaw in the model. Similarly the thickness of the K/T boundary layer, as predicted by this model, also matches the pattern seen in terrestrial sections and DSDP cores, discrepancies between the two being less than the local variability of the observed layer. Although the model again fails at distances less than 2000km, this suggests that the input values and relationships are approximately correct.

Results and Conclusions: The results can be plotted as energy per unit area against distance, along arcs of great circles through Chicxulub (fig. 1). These graphs show that $E \approx 10^{14} \cdot R^{-1.5}$, where E is the total kinetic energy of the ejecta (Jm^{-2}) and R is the distance from Chicxulub (km). Hence at a distance of 2100km the energy is typically $10^{9}Jm^{-2}$, but at 10000km, the energy is $10^{8}Jm^{-2}$. This represents an order of magnitude decrease and has important ramifications regarding the spatial variability of any associated extinctions.

The severity of the environmental (and hence biological) perturbation is not solely dependent on the total energy. The rate of arrival of ejecta i.e. the power of the IR pulse, is also critical. At 2100km from Chicxulub 90% of the ejecta arrives over a period of ≈1000s. At 10000km this value increases to ≈6000s. This is because at the proximal location the material has less far to travel to reach its destination and the low angle, low travel time ejecta curtain accounts for a significantly larger fraction of the total mass.

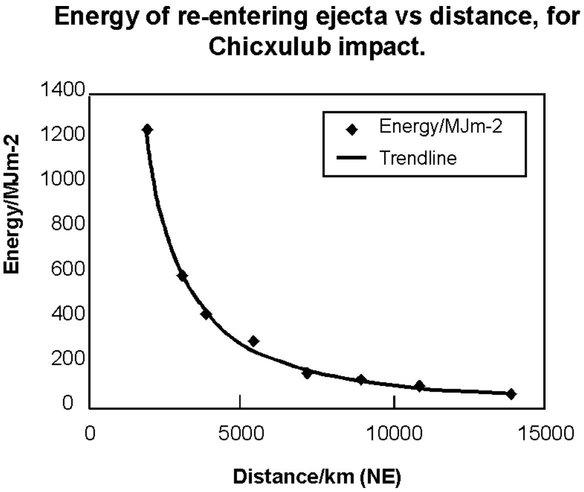

Fig. 1 The total energy deposition per unit area in the atmosphere, plotted against distance, along a great circle bearing northeast from the Chicxulub impact site.

The calculated peak power deposition in the atmosphere above New Zealand is $\approx 40kWm^{-2}$, however above New Mexico this value climbs to $\approx 2500kWm^{-2}$.

It is apparent from these results that the power and energy of the IR pulse are geographically heterogeneous and fall off rapidly with distance from Chicxulub. The way in which the environment is affected by this phenomenon is itself variable, depending on cloud cover and surface features. A large tropical cloud may require $5 \cdot 10^{7}Jm^{-2}$ to completely evaporate it. Thus, if $10^{8}Jm^{-2}$ are deposited in the atmosphere above a certain location, the cloud cover will be critical in determining the quantity of IR radiation that reaches the surface. Similarly, two identical doses of IR radiation, incident on two contrasting habitats, will have different effects on the resident biota. A marine environment may be relatively unaffected and rapidly repopulated, whereas the fragile equilibrium of a rain forest might be irretrievably disturbed, resulting in numerous extinctions.

This work suggests that IR radiation, caused by ejecta re-entry, is indeed a likely kill mechanism in large impact events and that it can generate considerable variation in extinction patterns, both in terms of geography and life habit.

References: [1] Alvarez L.W. et al. (1980) Science, 208, 1095-1108. [2] Morgan J. et al. (1997) Nature, 309, 472-476. [3] Melosh H.J. et al. (1990) Nature, 343, 251-254. [4] Whipple F.L. (1950) Proc. Natn. Acad. Sci. USA, 36, 687-695. [5] Alvarez W. et al. (1995) Science, 269, 930-935. [6] Housen K.R. et al. (1983) JGR, 88, B3, 2485-2499. [7] Vickery A.M. and Melosh H.J. (1990) GSA Spec. Pap. 247, 289-300. [8] Campos-Enriquez J.O. et al. (1998) Geophysics, 63, 5, 1585-1594. [9] Izett G.A. (1987) GSA Bulletin, 99, 78-86. [10] Thierstein et al. (1991) Proc. of the ODP, 119, 849-861. [11] Rehfeldt and Stoffler (1986) LPSL, 17. [12] Bohor B.F. (1990) GSA Spec. Pap. 247, 335-342. [13] Bostwick J.A. and Kyte F.T. (1996) GSA Spec. Pap. 307, 403-416.