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ARTICLE *in* EARTH AND PLANETARY SCIENCE LETTERS · FEBRUARY 1994

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Impact winter and the Cretaceous/Tertiary extinctions: Results of a Chicxulub asteroid impact model

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Received 19 September 1994; accepted 20 October 1994

Abstract

The Chicxulub impact crater in Mexico is the site of the impact purported to have caused mass extinctions at the Cretaceous/Tertiary (K/T) boundary. 2-D hydrocode modeling of the impact, coupled with studies of the impact site geology, indicate that between 0.4 and 7.0×10^{17} g of sulfur were vaporized by the impact into anhydrite target rocks. A small portion of the sulfur was released as SO_3 or SO_4, which converted rapidly into H_2SO_4 aerosol and fell as acid rain. A radiative transfer model, coupled with a model of coagulation indicates that the aerosol prolonged the initial blackout period caused by impact dust only if the aerosol contained impurities. A larger portion of sulfur was released as SO_2, which converted to aerosol slowly, due to the rate-limiting oxidation of SO_2. Our radiative transfer calculations, combined with rates of acid production, coagulation, and diffusion indicate that solar transmission was reduced to 10–20% of normal for a period of 8–13 yr. This reduction produced a climate forcing (cooling) of -300 Wm^{-2}, which far exceeded the $+8$ Wm^{-2} greenhouse warming, caused by the CO_2 released through the vaporization of carbonates, and therefore produced a decade of freezing and near-freezing temperatures. Several decades of moderate warming followed the decade of severe cooling due to the long residence time of CO_2. The prolonged impact winter may have been a major cause of the K/T extinctions.

1. Introduction

Alvarez and his colleagues [1] originally proposed that the large dust cloud from an asteroid or comet impact blocked out the sun and caused mass extinctions at the end of the Cretaceous. The recent recognition that the Chicxulub structure in northwestern Yucatan is this Cretaceous/Tertiary (K/T) impact site [2,3] allows us to refine the possible extinction mechanisms. A unique aspect of the Chicxulub crater is the presence of thick deposits of anhydrite ($CaSO_4$), which, when impacted, created a massive sulfuric acid aerosol cloud [4,5] that amplified environmental stresses beyond those proposed for the impact dust alone. We combine studies of the Chicxulub geology with a 2-D model of impact dynamics and a 1-D radiative transfer model to explore the biospheric effects of the sulfuric acid aerosol.

SSDI 0012-821X(94)00226-6

2. Crater geology

The size of the Chicxulub crater is not well constrained. Estimates, based primarily upon circular gravity anomalies, indicate a diameter of ~ 180 km [2,6] or 260–300 km [7]. Our analyses of the crater geology indicate a rim diameter of ~ 240 km [8].

A sequence of carbonates and anhydrites 2.0–2.5 km thick comprises the upper section of target rock near Chicxulub [9–11]. The sequence thickens to the northwest and the total thickness at the center of the impact may be > 2.5 km. The average anhydrite composition of the pre-impact sediments, as measured in exploratory oil wells near the crater rim [9], is ~ 60% (roughly equivalent to 1,200–1,500 m thickness). Nevertheless, this assessment is based primarily on well cuttings, which may overestimate anhydrite volume. Analyses of cores [10,11] from these same wells record massive anhydrites with interbedded carbonates up to 750 m thick in the lower section near the crater rim, but only minor amounts of anhydrite in the upper section.

3. Impact modeling

In our model of the Chicxulub impact we assume a cylindrical silicate bolide impacting perpendicular to the surface at 20 km/s. More complex bolide geometries and oblique trajectories are difficult to model and 20 km/s is a typical velocity for asteroids. Given the uncertainty of the size of the Chicxulub crater, we chose to model the formation of craters with diameters of 180 km and 300 km. When scaling laws are applied [12] these diameters correspond to bolide diameters of 10 km and 20 km for the two crater sizes. Recent studies [13] indicate an impactor diameter of 32 km, hence our estimates are conservative.

We used a 2-D hydrocode impact model of a two-layer target to estimate the anhydrite volume vaporized by the impact (Fig. 1). We chose a range of anhydrite volumes to account for the variable estimates of the target rock. This range is equivalent to a minimum thickness of 500 m and a maximum of 1,500 m. From the model results we calculated the shock pressures and the mass of sulfur vaporized (Table 1). Shock pressures rapidly decay near the surface, due to a lack of confining pressure, and a large volume of sediments are ejected without being vaporized.

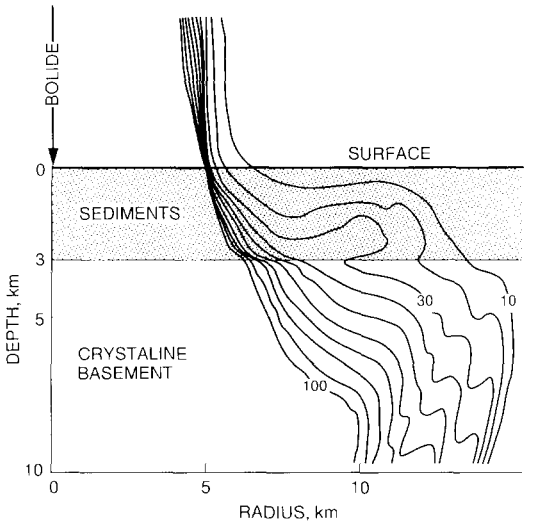

Fig. 1. Results of impact model for the 10 km diameter bolide impact (right half only, shock pressure isobars in GPa). The top layer was modeled as a wet tuff, which corresponds to the sedimentary layer at Chicxulub, and the bottom layer as granite, which corresponds to the basement metamorphics in this region. Center of impact at arrow. Experiments and theoretical studies indicate that shock-induced vaporization of anhydrite occurs between 50 and 100 GPa under gas release pressures of 1 bar [33,34]. The theoretical studies indicate that vaporization can occur at lower shock pressures if the gas release pressures are less than 1 bar. Therefore we assume all sediments shocked > 100 GPa are vaporized, and those shocked at > 30 GPa but < 100 GPa are partially vaporized. Results of the 20 km diameter bolide impact are nearly identical but with proportionally larger volumes of vaporized sediments. Computer code for impact simulation adapted from [35].

The sulfur is released as SO_2 and SO_3 [4,5]. A large volume of highly shocked (> 100 GPa) sediments lies directly beneath the bolide (Fig. 1) and our model predicts that it is released to the atmosphere after decompression (~ 10 s after impact), probably as SO_2. A smaller volume (~ 10–20%) of the highly shocked sediments lies outside of the bolide footprint and is released to the atmosphere rapidly. Laser experiments [14]

Table 1
Volume and mass of vaporized material

Bolide diameter (km)	Vaporized sediments (km^3)	Sulfur mass (g)
10	300–600	3.5×10^{16}–2.1×10^{17}
20	1100–2000	1.3×10^{17}–7.0×10^{17}

Impact model predictions of sediment volumes shocked > 30 GPa (larger volume) and > 100 GPa (smaller volume) for two possible Chicxulub bolide sizes. We assume that complete vaporization of the anhydrites occurs within this range of shock pressures. Corresponding minimum sulfur masses are for 500 m of anhydrite in the sedimentary layer shocked > 100 GPa, and maximum masses are for 1,500 m anhydrite shocked at > 30 GPa.

that simulate impact processes in this outer zone indicate that more SO_3 and SO_4 than SO_2 is produced. Nevertheless, the heat generated by such a large impact favors the decomposition of the SO_3 to SO_2 in the plume [5].

The volatiles separate from the melt due to rapid gas expansion [15] and due to gravitational forces [5]. Previous models of K/T impact dynamics have shown that the plume extends beyond the stratosphere [12,16]. Such models are corroborated by the recent observations of immense plumes generated by the Shoemaker–Levy 9 comet impact on Jupiter. Given the momentum of the plume material, very little sulfur would rain out in the vicinity of the impact. The global distribution of highly shocked ejecta found at the K/T boundary confirms that the dust cloud enveloped most of the Earth and we assume that a globally distributed sulfur cloud formed as well. Some of the sulfur may have recombined with the Ca-rich oxides in the dust plume but this was probably minor, because of the mechanical separation noted above and because the lifetime of the dust was < 6 months [17,18].

4. Atmospheric modeling

We examine two possible scenarios for the massive release of sulfur above the stratosphere, both of which assume rapid, global dispersion of the sulfur. The first is based on the assumption that the sulfur is rapidly converted to H_2SO_4 aerosol, which would occur if the dominant gas species is SO_3, or if chemical reactions in the plume produce H_2SO_4 directly. The second is based on the assumption that large quantities of SO_2 are produced, which must be oxidized by sunlight to form SO_3 prior to hydration to H_2SO_4. The two scenarios are not exclusive and both probably occurred.

We adapted a radiative transfer model originally designed for studies of planetary atmospheres [19] to investigate the solar flux through the H_2SO_4 aerosol cloud. Our model calculates the amount of sunlight reaching the ground, both directly and diffusely through the cloud, based on Mie scattering theory.

Our first scenario involves coagulation and sedimentation. We adapted the coagulation model proposed in previous K/T impact studies [17], which is based on particle collisions due to Brownian motion and 100% cohesion. An initial mean particle size of 0.5 μm was chosen, based on Pinatubo volcanic H_2SO_4 aerosol studies [20]. We experimented with smaller sizes but found that the model output was not very sensitive to smaller initial particles. The rapid formation of the H_2SO_4 aerosols permits acid nucleation on stratospheric dust and soot particles produced by the impact. Therefore, our model examines the effect of impurities by using different imaginary indices of refraction.

The results of a series of model runs is shown in Fig. 2. Model runs with larger aerosol loadings than the one shown produced lower transmission values at the outset but did not prolong the effects. This self-limiting processes is well known for large volcanic eruptions [21]. Our results indicate that light levels dropped below the photosynthesis limit for 6–9 months if the acid droplets were slightly darkened by impurities.

Our second scenario considers the conversion rate of SO_2 to H_2SO_4 aerosol. The model is constructed so that the H_2SO_4 aerosol is continuously produced photochemically in the upper stratosphere. The lower stratosphere is effectively shielded from the sun; hence H_2SO_4 does not form at lower levels. Coagulation and sedimentation processes cause the aerosol particle size and

number density, which were modeled in 12 stratospheric layers, to change as they fall. The choice of 12 layers was a compromise between limits on computational time and adequate characterization of changes in particle properties through the stratosphere. The resulting H_2SO_4 cloud properties represent quasi-steady-state conditions for the lifetime of the SO_2 cloud, whereby new particles form in the first layer as those in the 12th layer fall below 10 km and are removed.

Models of Earth [21] and Venus [22] indicate that the rate-limiting factor for aerosol production is the photochemical oxidation of SO_2, which is controlled by the abundance of UV light and oxidants. The SO_2 conversion rate is proportional

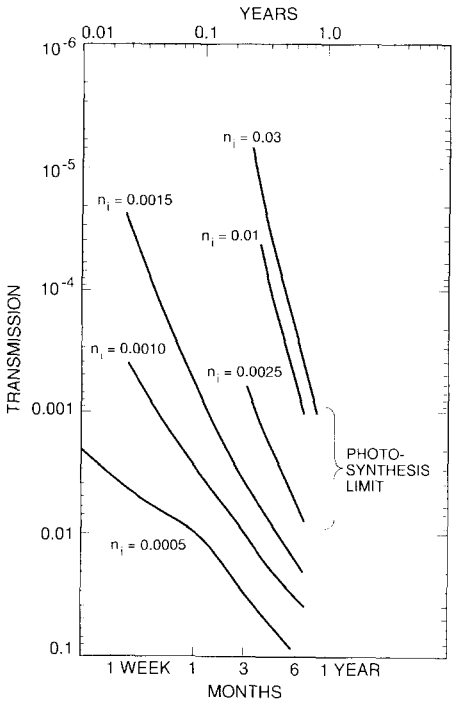

Fig. 2. Reduction in solar transmission at the Earth's surface over time for an initial H_2SO_4 aerosol loading between 20 and 30 km of 5×10^{15} g of sulfur, which is equivalent to only about 5% of our sulfur mass estimates. The curves are for different imaginary indices of refraction (n_i), which reflect possible impurities in the acid droplets: $n_i = 0.03$ = soot; $n_i = 0.0025$ = silicate dust; $n_i = 0.0005$ = pure H_2SO_4 aerosol. Photosynthesis ceases when transmission drops below 0.001–0.01 [17,36]. Once particles fall below 10 km we assume that they are removed immediately by meteorological processes.

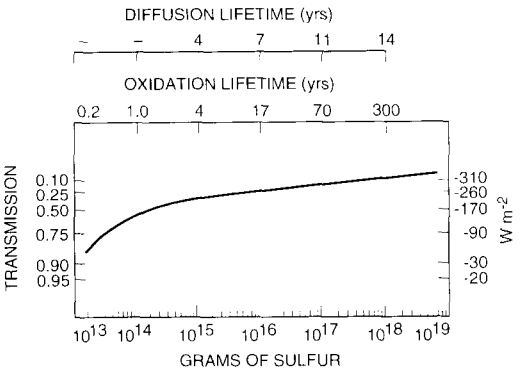

Fig. 3. Model predictions for the reduction in solar transmission at the Earth's surface and corresponding climate forcing (Wm^{-2}) for various sulfur initial masses. Climate forcing calculated for the top of the atmosphere with incident solar radiation of 340 Wm^{-2} [37]. Oxidation lifetimes are the time required to convert the given mass of sulfur into H_2SO_4 aerosol. Diffusion lifetimes are the time required to remove sufficient unoxidized SO_2 by diffusion to the troposphere to shut down acid production (this process is insignificant for short oxidation lifetimes). Once acid production ceases the aerosol cloud dissipates in about 1 yr.

to the volume. However, the rate increases more slowly than the volume, so that the rate doubles for an order of magnitude increase in SO_2, resulting in a 4–5 times increase in the lifetime [21]. The SO_2 oxidation lifetime for our upper sulfur estimate, derived by scaling-up volcanic conversion rates [21], is about 160 yr (Fig. 3). Applying the same scaling to our lower sulfur estimate yields an SO_2 oxidation lifetime of 24 yr, while smaller sulfur masses yield correspondingly shorter oxidation lifetimes. Our upper sulfur mass is comparable to the mass of sulfur in the atmosphere of Venus, which studies have shown has an oxidation lifetime of 200 yr [23]. This comparison suggests such scaling is reasonable, although one would expect slightly slower oxidation rates on Venus given the low abundance of oxygen in the atmosphere.

Our impact model indicates that the Chicxulub impact injected large amounts of water vapor into the stratosphere, probably a mass within an order of magnitude of that of sulfur (assuming a maximum 50 m water depth and 5% carbonate porosity). This water may have increased the abundance of oxidants but the effect on the oxidation

rate would be minor because the abundance of oxidants varies with the square root of the water concentration and because oxidation is inhibited by the shielding of UV by the SO_2 cloud [21] (a factor accounted for in our SO_2 lifetime estimates). Thus, rates may have increased slightly. Oxidants may have ultimately become depleted, thus reducing the H_2SO_4 production rate and extending the oxidation lifetime of the SO_2 cloud.

Given these long oxidation lifetimes, eddy and molecular diffusion will ultimately become important factors in removing unoxidized SO_2 from the stratosphere. Turnover of the stratospheric air mass has been calculated by various methods to be between 2.5 and 3.1 yr [24,25]. We used a diffusion e-folding time of 2.5 yr to estimate the minimum diffusion lifetime of the SO_2 cloud (Fig. 3). For atmospheric injections of $< 10^{15}$ g S diffusion is unimportant but for larger sulfur masses the diffusion lifetime becomes the effective lifetime of the sulfur cloud, because the SO_2 reservoir is depleted before oxidation is complete.

5. Conclusions

Our estimates of sulfate vaporization are similar to those of Brett [5] for a 180 km diameter crater, while the upper estimates of Sigurdsson et al. [6] are much too high. Neither of these previous studies considered craters larger than 180 km. Previous K/T impact models [17,18] predicted a 3–6 month blackout with freezing and disruption of photosynthesis due to the silicate dust. The rapid generation of H_2SO_4 aerosols may have slightly extended this blackout period to 6–9 months. The model results for the SO_2 scenario predict that solar transmission would drop to about 20–10% of normal for about 8–13 yr for our lower and upper sulfur estimates, respectively (Fig. 3). This is equivalent to that of a very cloudy day but is above the photosynthesis limit.

Greenhouse global warming caused by CO_2 released from the vaporized carbonates at Chicxulub must also be considered [26]. The mass of CO_2 released is about an order of magnitude more than the sulfur mass because carbonates were possibly more abundant and they vaporize at relatively low (10–40 GPa) shock pressures [26]. The climate forcing represented by an instantaneous release of 10^{19} g of CO_2, the maximum indicated by our model, is about 8 Wm^{-2}, which is equivalent to a 4°C warming above pre-impact temperatures [27]. This temperature increase is a maximum and would be less if smaller amounts of CO_2 were released or if terminal Cretaceous CO_2 levels were much higher than today's. This positive forcing, as well as the very slight greenhouse effect due to the SO_2 cloud [27] or water vapor [28], are insignificant compared to the -300 Wm^{-2} predicted for the impact vaporization of sulfates at Chicxulub (Fig. 3). Nevertheless, the 50–200 yr residence time of CO_2 [29] is greater than that proposed for the cooling event; therefore, temperatures rapidly rebounded to a few degrees Celsius above pre-impact levels following the initial cooling.

The -300 Wm^{-2} climate forcing proposed for the impact aerosols is equivalent to ~ 100°C cooling if a new equilibrium temperature were reached and no other feedbacks occurred [27]. However, the actual temperature drop would be buffered by heat released from the oceans for several years. Modeling of short-term impact-induced ocean cooling [30] suggests that significant cooling can occur in < 14 yr but precise estimates of temperature changes remain uncertain, due to poorly known Cretaceous circulation patterns, which were probably much different from today's [31].

Despite these uncertainties, significant global cooling must have occurred for a decade after the impact, followed by a more prolonged period of moderate warming. A brief episode of cooling of the oceans' surface, followed by a much longer episode of warming, has been proposed independently from stable isotope studies of early Tertiary marine organisms [32]; however, it is difficult to resolve events on timescales of decades to centuries in the geological record. Spatial patterns are more readily examined. We hypothesize that biota in continental regions were severely stressed by the impact, due to freezing. Coastal and island areas probably became temperate

refugia for terrestrial biota and survivors may have been species with access to the refugia and the ability to survive a prolonged period of constricted habitat. Marine extinctions may have been related to an organism's ability to survive the initial photosynthesis blackout, perhaps by undergoing a dormant state for several months, and its tolerance of ocean cooling. These hypotheses can be tested by future paleontological research.

Acknowledgements

This work was funded by the Exobiology Program of the National Aeronautics and Space Administration. *[MK]*

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