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BIOSPHERIC EFFECTS OF A LARGE EXTRATERRESTRIAL IMPACT: CASE STUDY OF THE CRETACEOUS/TERTIARY BOUNDARY CRATER

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SUMMARY

The Chicxulub impact crater, buried in the Yucatan carbonate platform in Mexico, is the site of the impact purported to have caused mass extinctions at the Cretaceous/Tertiary (K/T) boundary. Geophysical and remote sensing research suggests that the crater diameter is greater than 220 km. A recently discovered Chicxulub ejecta deposit in Belize contains evidence of carbonate vaporization and precipitation from the vapor plume. Sulfate clasts are almost absent in the Belize ejecta, but are abundant in the coarse ejecta near the crater rim, which may reflect the greater abundance of sulfates deep in the target section. The absence of sulfate precipitates in Belize may indicate that most of the vaporized sulfur was deposited in the upper atmosphere. Hydrocode modeling of the impact indicates that between 0.4 to 7.0 x 10^{17} g of sulfur were vaporized by the impact in sulfates. Laser experiments indicate that SO_2, SO_3, and SO_4 are produced, and that complex chemical reactions between plume constituents occur during condensation. The sulfur released as SO_3 or SO_4 converted rapidly into H_2SO_4 aerosol. A radiative transfer model coupled with a model of coagulation predicts that the aerosol prolonged the initial blackout period caused by impact dust only if the it contained impurities. The sulfur released as SO_2 converted to aerosol slowly due to the rate limiting oxidation of SO_2. Radiative transfer calculations combined with rates of acid production, coagulation, and diffusion indicate that solar transmission was reduced to 10-20 percent of normal for a period of 8-13 years. 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.

INTRODUCTION

The evolution of life on Earth has been punctuated by several biological crises represented by mass extinctions in the paleontological record (e.g. Raup and Sepkoski 1982, 1986; Sepkoski 1990). These crises mark major shifts in evolutionary trends and play a critical role in the evolutionary process. Although recent advances have greatly improved our knowledge of the chronology, scale, and structure of mass extinctions, causes remains poorly understood. The best studied cause of a major biological crises is the one proposed by Alvarez et al. (1980), who hypothesized that the dust cloud from an asteroid or comet impact caused the mass extinction that marks the end of the Cretaceous Period. The decade of research following the presentation of the Alvarez hypothesis produced substantial support (e.g. Alvarez and Asaro 1990). The recent recognition that the Chicxulub crater in the Yucatan Peninsula of Mexico is the site of the K/T impact (e.g. Hildebrand et al. 1991; Hildebrand 1993; Pope et al. 1991, 1993; Sharpton et al. 1992, 1993; Swisher et al. 1992) has provided the final confirmation that a major impact, perhaps the largest in the Phanerozoic, occurred at the K/T boundary.

While the impact portion of the Alvarez hypothesis is now widely accepted, the second part, that of a causal link between the impact and mass extinctions, remains controversial and in need of rigorous testing. The controversy is not surprising, given the inherent complexities of biological systems and their response to external forces (Jablonski 1994). Furthermore, previous studies of the K/T extinctions were impeded by a lack of constraints on the nature of the impact, which led to a seemingly endless list of possible extinction mechanisms. The discovery of the Chicxulub crater provides an ideal opportunity to constrain these possible mechanisms. In 1992 we began such a study of extinction mechanisms with support from the NASA Exobiology Program. Our project is an interdisciplinary one that combines studies of the crater geology with models of impact and atmospheric dynamics. We have focussed the study on the biospheric effects of volatiles, primarily sulfur gases, released by the impact into carbonate and evaporite terrain. The results of the FY 1994 research are summarized below, followed by a discussion of future work.

CRATER SIZE

Our geological research on the Chicxulub crater has concentrated on delineating the morphology of the crater with a remote sensing and field-based study of surface features combined with a modest geophysical research effort. Determination of the size of the Chicxulub crater is important for our study of the biospheric effect largely because it will help us quantify the mass of material ejected into the stratosphere. We have expanded upon our (Pope et al. 1991) earlier studies of a ~170 km diameter ring of sink holes (known locally as cenotes) that is concentric with the gravity and magnetic anomalies associated with the crater. These new analyses, based on a re-evaluation of data from exploratory oil wells drilled by PEMEX and their relationship to the Cenote Ring (Fig. 1), indicates a crater diameter of ~240 km (Pope et al. 1993). Two crater size estimates have been published by other researchers, based on the gravity and magnetic surveys: 170-180 km (Hildebrand et al. 1991; Pilkington et al. 1994), and 260-300 km (Sharpton et al. 1993). All of these studies concur that there is a prominent circular feature with a diameter of 170-180 km. The main disagreement is whether this feature is the final crater rim after relaxation and slumping, or the limit of maximum deformation associated with the rim of the transient crater (initial excavation cavity), which is roughly equivalent to the floor of the final crater.

Recent seismic profiles published by Camargo and Suarez (1994) confirm that the main Tertiary basin created by the impact is about 160-170 km in diameter, and that slump blocks related to possible ring faults extend to diameters of about 220 km. These blocks extend to the edge of the profiles and therefore ring faults at larger diameters are possible. These new data suggest that the final crater rim may be greater than 220 km. Likewise these data appear to constrain the diameter of the transient crater to 170 km or slightly less, which is most consistent with the larger crater estimates of Pope et al. (1993) and Sharpton et al. (1993).

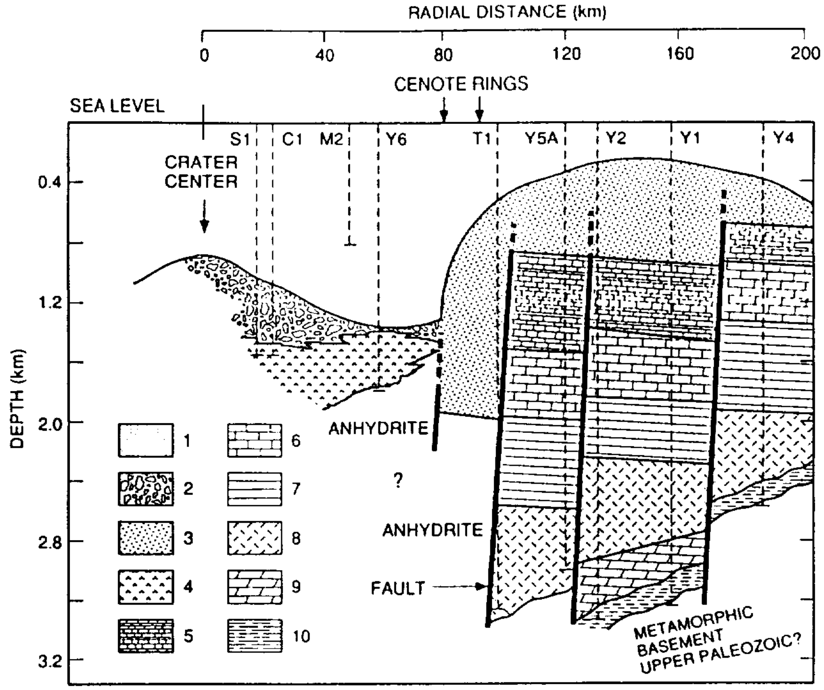

Fig. 1. Subsurface geology of the Chicxulub structure (adapted from Pope and others, 1993). Data from exploratory oil wells drilled by Petroleos Mexicanos are plotted as a function of their radial distance from the center of the crater inferred from the center of the Cenote Ring (a semi-circle of sink holes that apparently demarcates the floor of the crater - see Pope and others, 1991). Vertical exaggeration is 50 times. Stratigraphy of Yucatan 1 (Y1), Yucatan 2 (Y2), Yucatan 4 (Y4), Yucatan 5A (Y5A), Yucatan 6 (Y6) are from Marshal (1974) as modified by Weidie (1985). Stratigraphy and correlations from Sacapuc 1(S1), Chicxulub 1 (C1), and Ticul 1 (T1) are our own, based on stratigraphic profiles presented by Lopez Ramos (1979), and an unpublished version by G.E. Murray, A.A. Meyerhoff, and A.E. Weidie provided to us by A.E. Weidie. Thickness of unit 3 in Ticul 1 based on interpretations by Sharpton and others (1994). Thickness of Tertiary section and information on Merida 2 (M2) from Lopez Ramos (1979). All faults are inferred from offset of beds except the one recorded in drill logs of the Ticul 1 well. Fault closest to the crater floor are interpreted as ring faults and more such faults may lie between those designated. Key (interpretations in parentheses): 1 - Tertiary marine sediments, (including some crater slump deposits near the base, 2 - Bentonitic breccia (impact breccia and suevite). 3 - Conglomerate and breccia composed of angular to rounded pebble-sized detritial clasts of anhydrite, dolomite, and limestone in a dolomitic micrite matrix (impact ejecta including continuous deposit from secondary impacts an possibly collapse of the transient crater rim in T1). 4 - Crystalline melt rocks and glass (impact melt sheet). 5 - Upper Cretaceous mollusk, pelletoid micrite and laminated fossiliferous dolomite. 6 - Lower Cretaceous pelleted rudist biomicrite, biosparite, milinoid pelmicrite with anhydrite interlaminae. 7 - Lower Cretaceous laminated dolomite. 8 - Lower Cretaceous anhydrite. 9 - Lower Cretaceous milinoid dolomite and quartz-silty dolomite, 10 - Jurassic (?) arenite, shale, anhydrite, and dolomite. The bottom 10 m of Y6 and the lower half of T1 contain anhydrite, but the stratigraphy between these two wells is not well constrained.

REMOTE SENSING

The research outlined above has helped focus our remote sensing work on the region between the proposed 180 km and 300 km diameters. A partial second ring was found with Landsat TM imagery in the southwest portion of the crater at a radius of ~90 km (Pope et al. 1993), which adds support to our earlier interpretations of ring faults in this region. No other concentric feature has yet been identified on the Landsat TM images.

SIR-C/X-SAR images of the NW coast of the Yucatan Peninsula were acquired by the space shuttle Endeavour in October 1994. SIR-C L band images show the two Cenote Rings (Fig. 2). These images also show areas of ground water discharge (springs), which are present near the proposed peak ring (r=53 km, Sharpton et al. 1993), but are most abundant near the 240 km diameter crater rim proposed by Pope et al. (1993). Fossil Late Tertiary beach ridges (Fig. 2) extend southward from the Cenote Rings and are associated with the proposed location of the peak ring. These ridges may reflect shoaling along topographic highs related to the buried crater structure. The ground water discharge areas may also reflect buried crater structures (faults? ring crests?) with higher permeability.

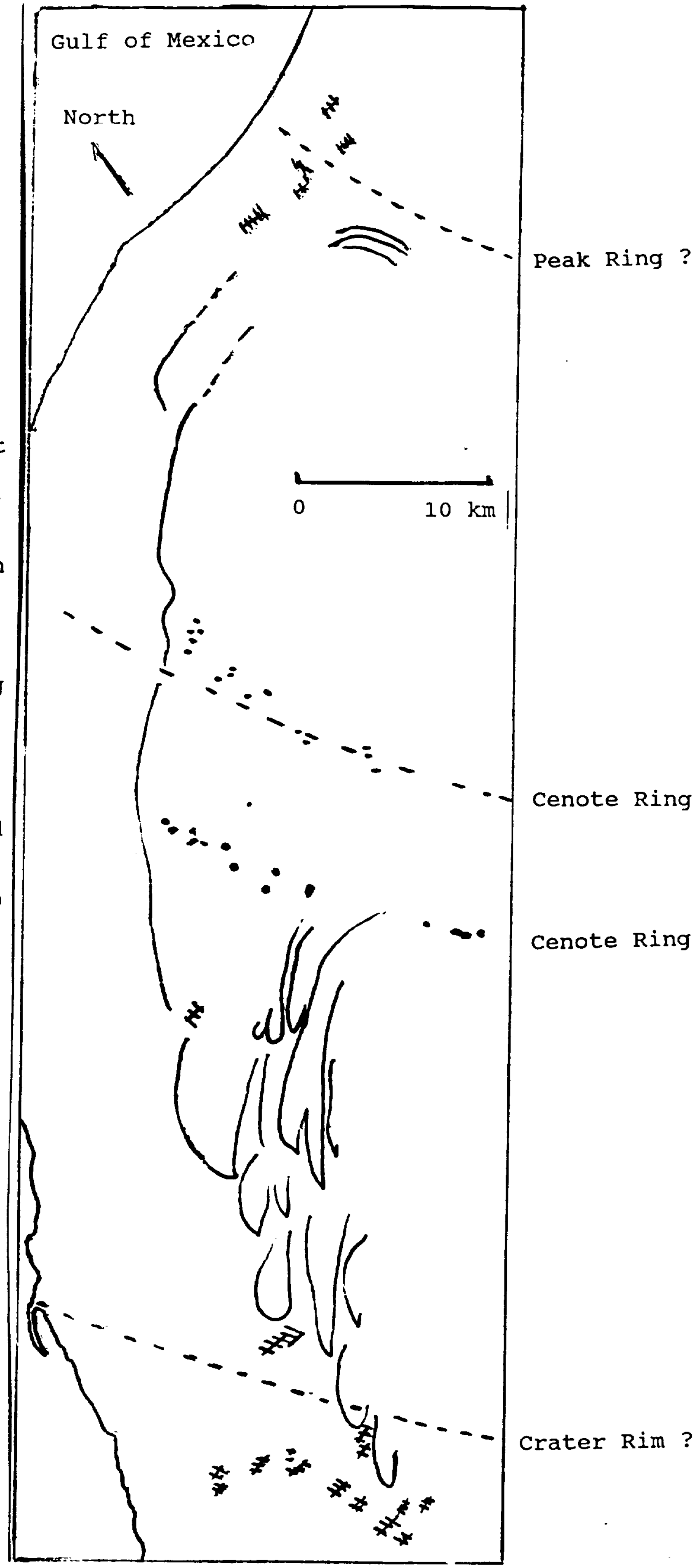

Figure 2. Map of the geomorphology/hydrology of the southwest portion of the Chicxulub crater based on interpretation of SIR-C L band imagery acquired by the space shuttle Endeavour in October 1994. Shown are two Cenote (sink hole) Rings near the center of the image, the inner most of which demarcates the crater floor (Pope et al. 1991; 1993). The inner ring is the most continuous and has a mean radius of ~83 km, the trace of which is marked by the dashed line. Nearly the full, known extent of the second ring is shown on the map and lies just outside the main ring at a radius of ~90 km. Also marked by dashed lines are the locations of the proposed peak ring (r=53 km, Sharpton et al. 1993), and the crater rim (r=120 km, Pope et. al. 1993). Cross-hatched areas mark ground water discharge zones (springs): present near the proposed peak ring, but most abundant outside the Cenote Rings, especially near the proposed crater rim. Springs are also associated with the fossil Late Tertiary beach ridges (lobate and linear features), which are abundant between the Cenote Rings and the crater rim, and near the peak ring.

GEOPHYSICAL RESEARCH

In collaboration with the Instituto Mexicano de Petroleo we undertook a gravity and magnetics survey in 1994 of the coastal region encompassing the southwestern portion of the crater rim within the 180-300 km diameter contested region noted above (Kinsland et al. 1994). This is the region where the surface expression of the crater (i.e. the Cenote Ring) is the most pronounced, yet it is an area where there are few gravity data (Sharpton et al. 1993). Data from the new profile are shown in Figure 3, along with the interpolated profile from Sharpton et al. (1993). These new data do not support the presence of a gravity high ("fourth ring") at the diameter of 260-300 km as proposed by Sharpton et al. (1993). There are several minor low gravity anomalies (Fig. 3) at approximate diameters of 226, 246, 268, and 292 km, that may be related to the buried crater, but this is very speculative. More work is needed to determine if these lows are concentric to the crater.

TARGET AND EJECTA DEPOSITS

Our study of the Chicxulub target lithologies has concentrated on an examination of published and unpublished reports from the PEMEX exploratory wells, and on a recently discovered Chicxulub proximal ejecta deposit in Belize (Ocampo and Pope 1994; Ocampo et al. in press). Of primary interest are the thickness and

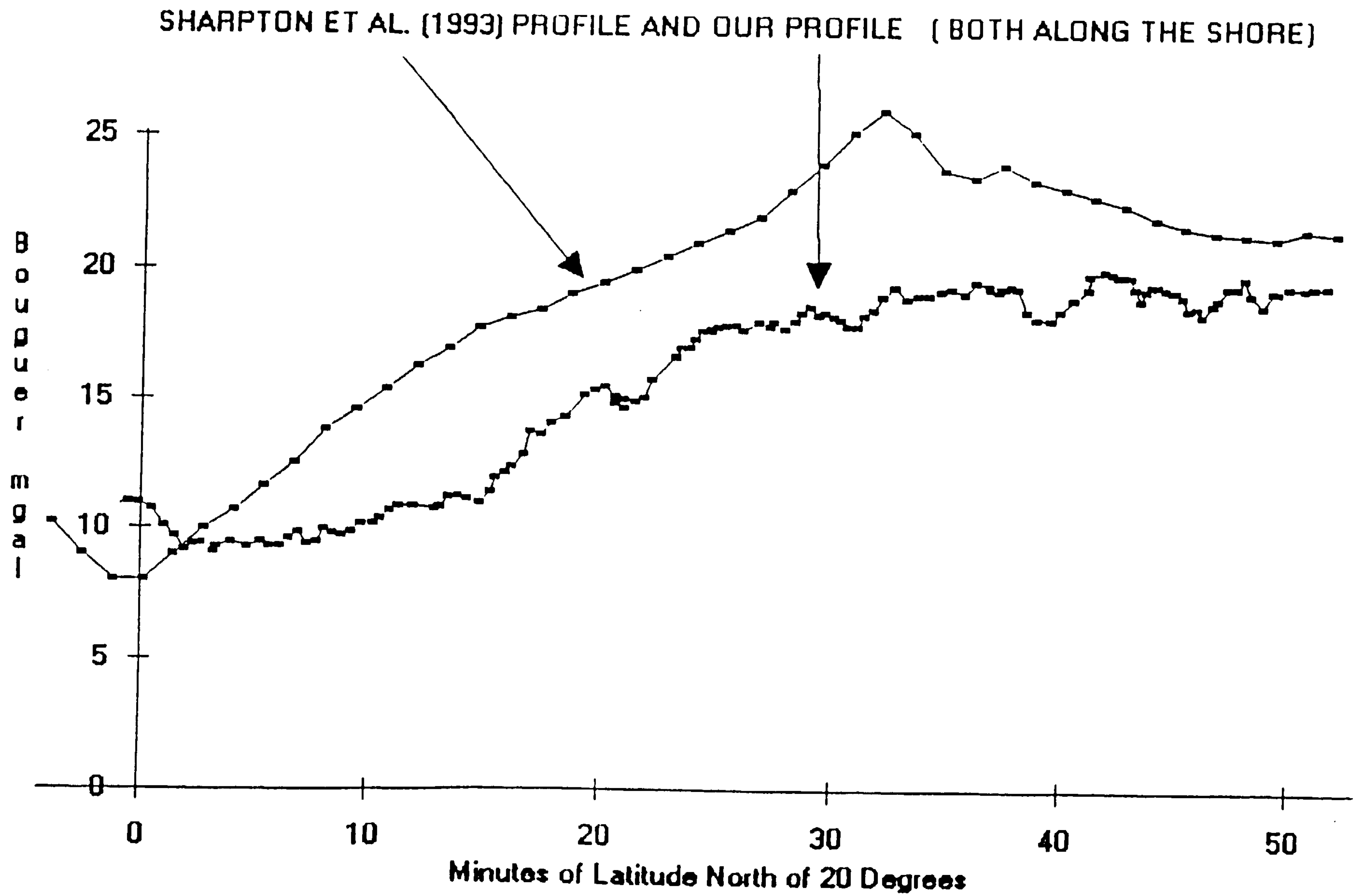

Figure 3. Bouguer gravity profile along west coast of the Yucatan Peninsula (Celestun to Campeche). Measurements taken every 0.5 km. Peak in the Sharpton et al. (1993) profile at 20° 33' lies at the approximate location of the 300 km diameter "fourth ring".

composition of the sediments that are the source of the volatiles whose biospheric effects we wish to evaluate. Analyses of data from well cuttings indicate 60% anhydrite or gypsum and 40% carbonate in the 2.5 km section (Lopez Ramos 1979; Murray et al. n.d.), while analyses of the more limited core samples record only about 20-30% anhydrite (Marshall 1974; Weidie 1985). This discrepancy in anhydrite thickness has not been resolved.

In 1991 we discovered a K/T boundary deposit on Albion Island, Belize that subsequent analyses have shown to be the most proximal, exposed section of ejecta from the Chicxulub crater yet studied (Ocampo and Pope 1994; Ocampo et al. in press). Study of this deposit is just beginning, but it holds great promise for providing empirical data on the Chicxulub target lithology and sediment vaporization history. The Belize ejecta is composed of a spheroid bed and a diamictite bed, that we interpret as being deposited by the vapor plume (spheroid bed) and by ballistic sedimentation coupled with debris flow processes (diamictite) (Ocampo et al. in press). Many of the carbonate clasts have altered rims that may indicate exposure to high temperatures and subsequent partial vaporization. Preliminary microprobe analyses indicate that the dolomite matrix and spheroids are unusually rich in calcium, which is consistent with high temperature crystallization. Some or most of the carbonate spheroids may have originated as CaO and MgO ejecta produced during the vaporization of sulfates and carbonates, altered to carbonate in the plume or after deposition (CaO and MgO are unstable). Alternatively, the spheroids may represent condensates from the plume, as is suggested by the concentric banding of coarse and fine crystalline carbonate found in most large spheroids. These spheroids and alteration rims provide an ideal opportunity to investigate impact devolitilization of the sediments.

It is interesting to note that the Belize ejecta deposits contain almost no sulfate. It is possible that the sulfates, which are more soluble than carbonates, have been leached out. Voids around clasts are quite common, which may have originally contained sulfate coatings, however there is no evidence of massive sulfate removal. Our impact model suggests that coarse ejecta far from the crater are mostly derived from the upper-most strata of the target rock, which contain dolomites with little to no sulfate. This aspect of cratering dynamics probably explains the lack of sulfate clasts, which are abundant in the coarse ejecta drilled near the crater rim (Pope et al. 1993).

IMPACT MODELING OF SULFATE VAPORIZATION

We combined studies of the Chicxulub geology described above with a 2-D model of impact dynamics adapted from hydrocode model of Amsden et al. (1980) to a simulate an asteroid impact into a two layer target (Fig. 4) (Pope et al. 1994). We assumed a cylindrical silicate bolide impacting perpendicular to the surface at 20 km/s.

Given the uncertainty of the size of the crater discussed above, we chose to model the formation of craters with diameters of 180 km and 300 km. When scaling laws are applied (Roddy et al. 1987) the two diameters conservatively correspond to bolide diameters of 10 km and 20 km. To account for the range of anhydrite thicknesses noted above, we modeled thicknesses of 500-1500 m. From the model results we calculate shock pressures and the mass of sulfur vaporized (Table 1). Previous work indicates that the sulfur is released as SO_2 and SO_3 (Brett 1992; Sigurdsson et al. 1992). A large volume of highly shocked (>100 GPa) sediments lies directly beneath the bolide (Fig. 4), which is released to the atmosphere after decompression (~10 sec 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 (Gerasimov et al. 1994) that simulate impact processes in this outer zone indicate that SO_3, SO_4 and SO_2 are produced. Vapor plume condensation profiles (Fig. 5) indicate near complete sulfur degassing at the outset (low Ca/S ratios), with progressively more condensation of sulfur as the plume cools such that late stage condensates have Ca/S ratios similar to the target sulfates (~1). Differences in plume constituents produced in air and He, and by vaporization of anhydrite versus gypsum, emphasizes the role of atmospheric oxygen (oxidation of SO_2 to SO_3) and target water (sulfur reduction) respectively.

TABLE 1 Volume and Mass of Vaporized Material

Bolide Diameter km	Vaporized Sediments km^3	Sulfur Mass g
10	300-600	$3.5 \times 10^{16} - 2.1 \times 10^{17}$
20	1100-2000	$1.3 \times 10^{17} - 7.0 \times 10^{17}$

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 >30 GPa.

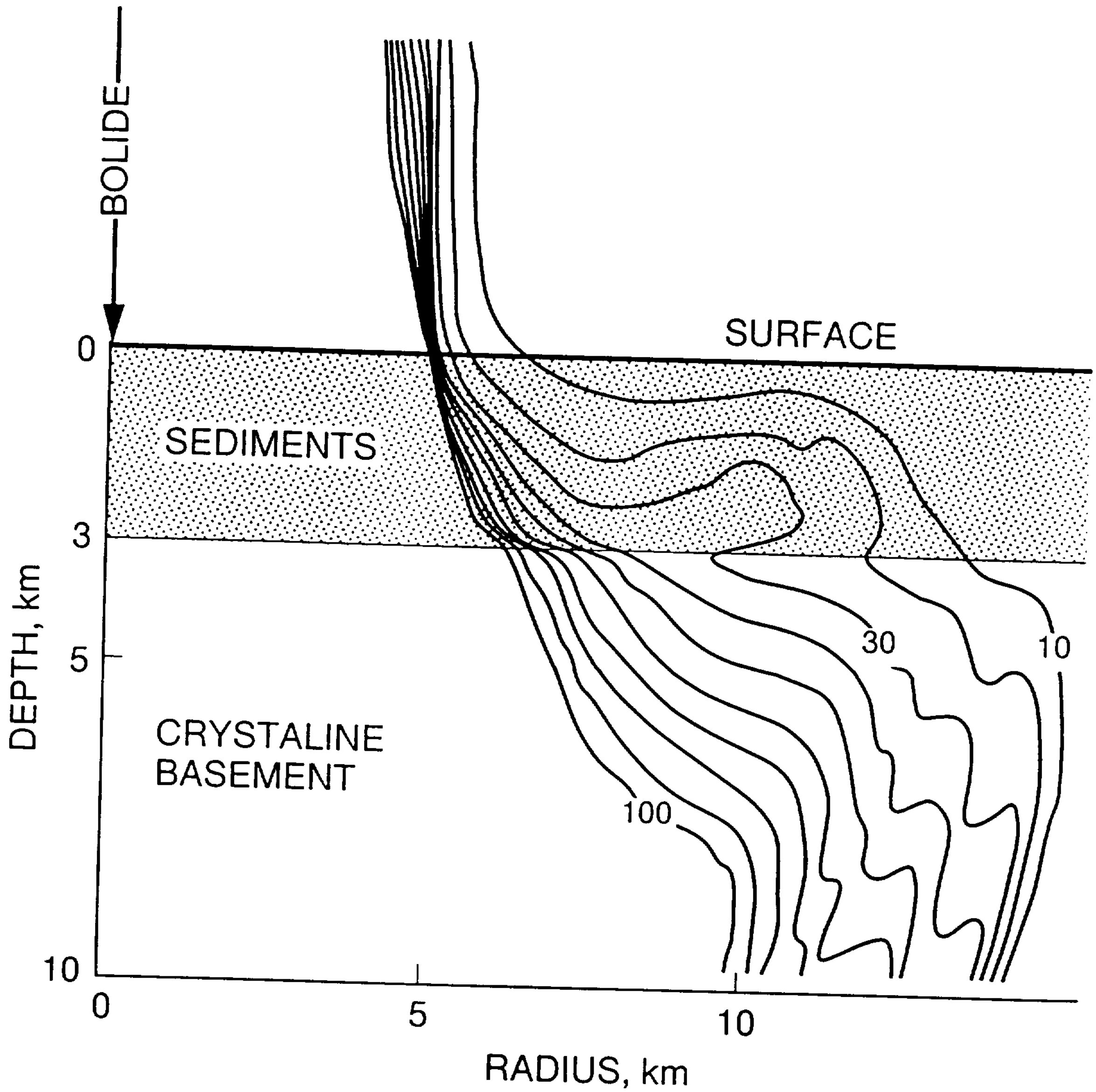

Figure 4. Results of impact model for the 10 km diameter bolide impact (right half only, shock pressure isobars in GPa). The top layer was modeled as a wet tuff, which corresponds the sedimentary layer at Chicxulub, and the bottom layer as granite, which corresponds to the basement metamorphics in this region. Center of impact at arrow. Experiments and theoretical studies indicate that shock-induced vaporization of anhydrite occurs between 50-100 GPa under gas release pressures of 1 bar (Chen and Ahrens 1993; Tyburczy and Ahrens 1993). 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 >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.

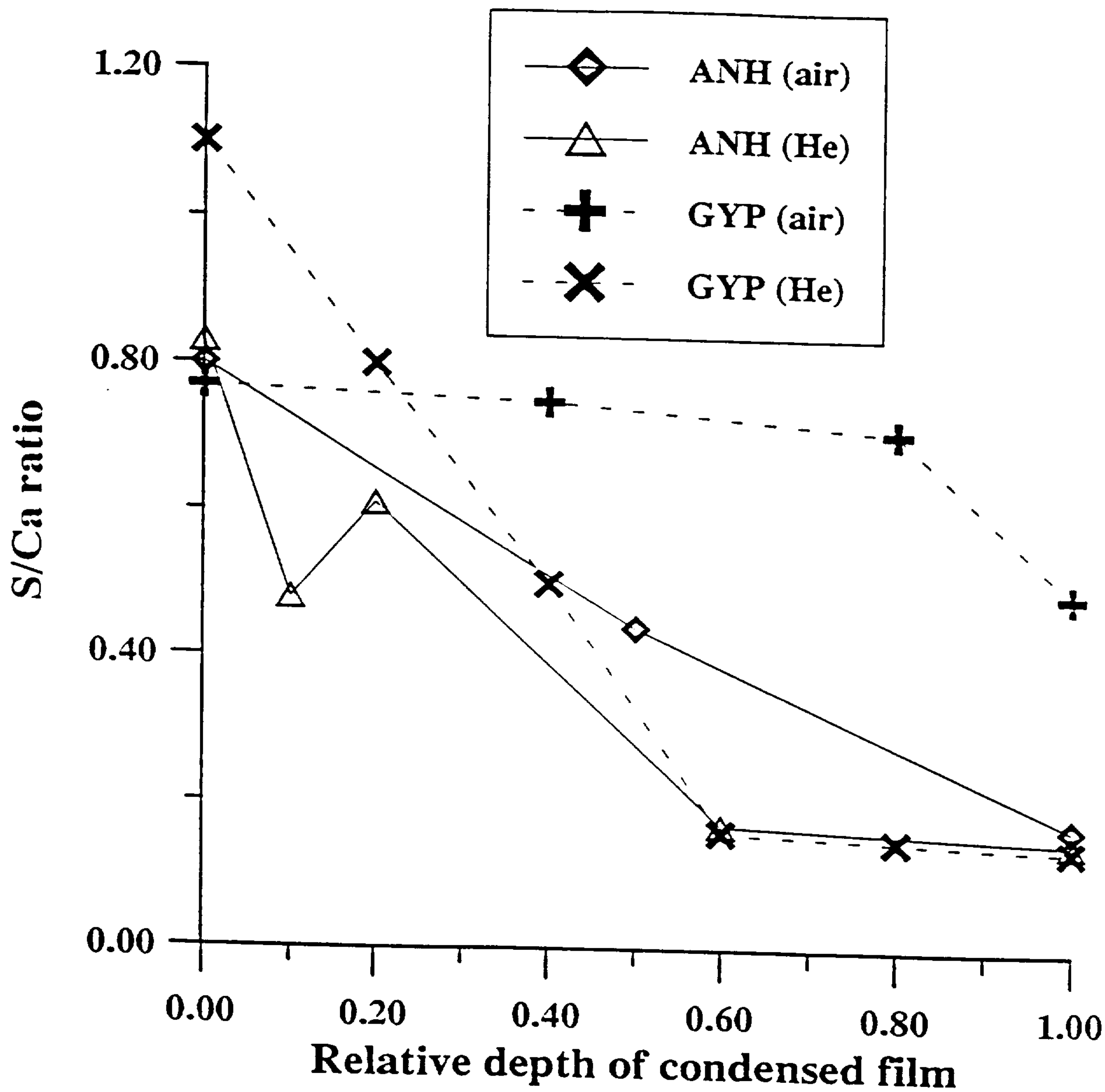

Fig. 5 *S/Ca* ratio profiles across condensed films for laser pulse vaporization of anhydrite((ANH) and gypsum (GYP) in the experimental cell filled with air and helium. Outer layers of condensed films (small relative depths), which are formed later in time by precipitation from a cooled vapor cloud, have *S/Ca* ratio notably higher than the deeper parts (at a high relative depth) of the film, which are precipitated from the early hot vapors.

ATMOSPHERIC MODELING

We examined 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. For scenario #1, we adapted a radiative transfer model (Baines and Smith 1990), and a coagulation model proposed in previous K/T impact studies (Toon et al. 1982), to investigate the solar flux through an instantaneous, globally distributed H_2SO_4 aerosol cloud. For scenario #2, our model is constructed such that the H_2SO_4 aerosol is continuously photochemically produced in the upper stratosphere. Coagulation and sedimentation processes cause the aerosol particle size and number density to change as they fall, which were modeled in 12 stratospheric layers. 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. SO_2 oxidation lifetimes are derived by scaling-up volcanic conversion rates (Pinto et al. 1989). Given these long oxidation lifetimes, eddy and molecular diffusion will ultimately become important factors in removing unoxidized SO_2 from the stratosphere. We used a diffusion e-folding time of 2.5 years to estimate the minimum diffusion lifetime of the SO_2 cloud. 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.

CONCLUSIONS

Our estimates of sulfate vaporization are similar to those of Brett (1992) for a 180 km diameter crater, while the upper estimates of Sigurdsson and colleagues (1992) are much too high. Neither of these previous studies considered craters larger than 180 km. Previous K/T impact models (Toon et al. 1982; Pollack et al. 1983) predicted a 3-6 month blackout with freezing and disruption of photosynthesis due to the silicate dust. Our model indicates that the rapid generation of H_2SO_4 aerosols may have slightly extended this blackout period to 6-9 months if they contain impurities (Fig. 6). The model results for scenario #2 predict that solar transmission would drop to about 20 to 10 percent of normal for about 8 to 13 yrs for our lower and upper sulfur estimates respectively (Fig. 7).

Greenhouse global warming caused by CO_2 released from the vaporized carbonates at Chicxulub must also be considered (O'Keefe

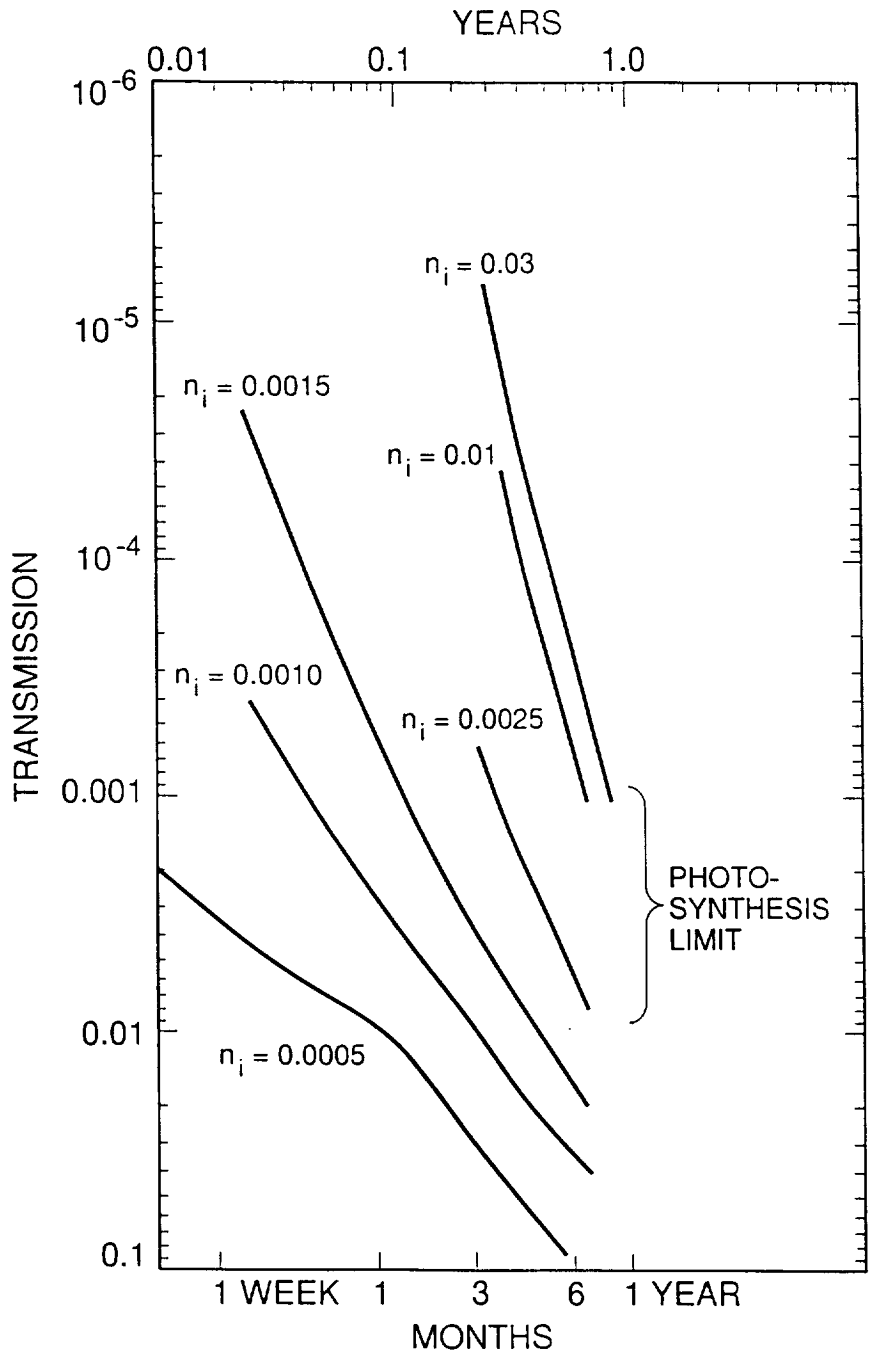

Figure 6. Reduction in solar transmission at the Earth's surface over time for an initial H_2SO_4 aerosol loading between 20 and 30 km of 5 x 10^{15} g of sulfur, which is equivalent to only about 5% of our sulfur mass estimates. Curves for different imaginary indices of refraction (n_i), which reflect possible impurities in the acid droplets. Soot n_i = 0.03; silicate dust n_i = 0.0025; pure H_2SO_4 aerosol n_i = 0.0005. Photosynthesis ceases when transmission drops below 0.001-0.01 (Gerstal and Zardecki 1982; Toon et al. 1982). Once particles fall below 10 km we assume that they are removed immediately by meteorological processes.

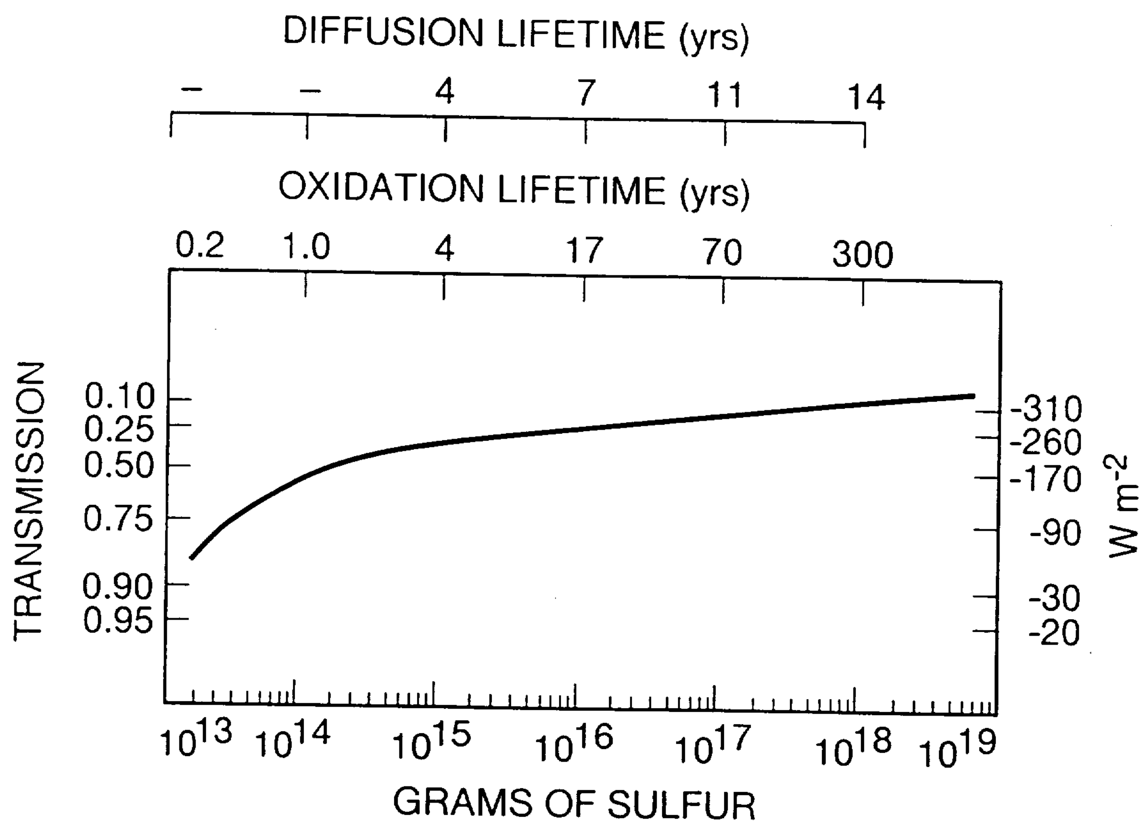

Figure 7. Model predictions for the reduction in solar transmission at the Earth's surface and corresponding climate forcing (Wm^{-2}) for various sulfur initial masses. Climate forcing calculated for the top of the atmosphere with incident solar radiation of 340 Wm^{-2} (Cubasch and Cess 1990). Oxidation 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 year.

and Ahrens 1989). 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 (Shine et al 1990). This positive forcing is insignificant compared to the -300 Wm^{-2} predicted for the impact vaporization of sulfates at Chicxulub (Fig. 7). Nevertheless, the 50-200 yr residence time of CO_2 (Watson et al. 1990) is greater than that proposed for the cooling event, therefore temperatures rapidly rebounded to a few °C 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 (Shine et al. 1990), but the actual temperature drop would be buffered by heat released from the oceans for several years. 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 be 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.

FUTURE RESEARCH

Our previous research has shown that uncertainties in the crater diameter, anhydrite thickness, and threshold of shock decomposition of anhydrite result in a factor of 20 uncertainty in the amount of sulfur vaporized. While efforts to improve constraints on the size of Chicxulub and the composition of the target material are continuing, our research has identified new issues that must be addressed as well as new opportunities to test our models.

We found that the drop in solar transmission is severe for all possible cases in our Chicxulub impact simulations. The key to the biospheric effect of the sulfur cloud is its duration, which given the large masses involved, is primarily controlled by the sulfuric acid production rate. This production rate is in turn largely controlled by the oxidation state of the sulfur gas released by the impact. SO_3 converts rapidly to H_2SO_4 aerosol, while SO_2 takes much longer due to the rate limiting oxidation. In our current models, we assume that both SO_3 and SO_2 are produced, and that SO_2 is more abundant. This assumption needs to be examined more thoroughly with future research.

A second assumption in our current models is that the sulfur cloud was rapidly dispersed around the globe. Recent studies indicate a possible latitudinal gradient in marine extinctions with high latitudes less affected (e.g. Barrera and Keller 1994; Elliot et al. 1994). This may reflect partial rather than complete global dispersion of the sulfur cloud due to the rapid sedimentation of aerosols or oblique impact. Observations of the evolution of aerosols in the impact plume of comet Shoemaker-Levy 9 (e.g. Orton et al. in review; West et al. in review), which struck Jupiter in July 1994 have led to the development of empirically verified microphysical models of ejecta plumes that can be applied to the Chicxulub case. This is an important opportunity that was not available when our study began. A third assumption of our current models is that the impact was vertical. A recent study by Schultz (1994) suggest that the Chicxulub impact was oblique (~30^{o}) from the southeast, maximizing biospheric effects in the northern hemisphere. Our impact model needs to be better coupled with our atmospheric microphysical model to explore the spatial dimension of the biospheric effects, and it needs to be modified to 3-D capability to assess the effects of oblique impact.

Our current predictions of the role of volatiles in the Chicxulub impact need to be empirically verified. The Belize ejecta deposits noted above provide a unique opportunity for this verification. For example, preliminary observations of the relative abundances of anhydrite/gypsum in ejecta from Belize versus near the crater rim can be used to verify our estimates of target lithologies and proposed impact dynamics. Of special importance is our interpretation of the spheroid bed in Belize as a vapor plume deposit. The possibility that much of the carbonate in this deposit represents the "back reaction" of impact produced oxides and CO_2 is of critical importance to our estimates of volatile production. Likewise the apparent lack of sulfates tentatively suggests significant sulfur degassing to the upper atmosphere with little precipitation of sulfate directly from the expanding plume. We need to examine further the evidence for high temperature vaporization and precipitation in this deposit.

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