I have presented evidence for the presence in the Cretaceous-Tertiary boundary clay of debris from a major meteorite impact on the earth 65 million years ago. If the observed 7 to 8 percent meteoritic debris was uniformly distributed globally within the 2 cm of boundary clay, I infer that the meteorite that struck the earth was 11 km in diameter and weighed 2500 billion tons (*16*). Perhaps this meteorite impact was largely responsible for the catastrophe at the end of the Cretaceous Period. If the eruption of the Tamboro volcano in the Dutch East Indies (Indonesia) caused the year 1816 to be "without a summer" in the New England states and caused famine and epidemic in Bengal (*17*), it is conceivable that a combination of primary and secondary effects stemming from the impact of a giant meteorite could have had devastating effects on life on this planet. Further studies on the worldwide distribution of meteoritic debris in the boundary layers of different geological periods should help us better understand the role played by the impact of celestial bodies on the evolution of life on the earth (*18*).

R. GANAPATHY

Research Laboratory,
J. T. Baker Chemical Company,
Phillipsburg, New Jersey 08865

References and Notes

1. S. Gartner and J. P. McGuirk, *Science* **206**, 1272 (1979).
2. *The Express*, Easton, Pa., 31 May 1979; *Chem. Eng. News* **57**, 7 (1979); *ibid.* **58**, 25 (1980).
3. R. Ganapathy, R. R. Keays, J. C. Laul, E. Anders, *Geochim. Cosmochim. Acta Suppl. 1* (1970), p. 1117; R. Ganapathy, J. W. Morgan, U. Krähenbühl, E. Anders, *ibid.*, *Suppl. 4* (1973), p. 1239; J. W. Morgan, R. Ganapathy, H. Higuchi, U. Krähenbühl, E. Anders, *ibid.*, *Suppl. 5* (1974), p. 1703; R. Ganapathy, D. E. Brownlee, P. W. Hodge, *Science* **201**, 1119 (1978); R. Ganapathy and D. E. Brownlee, *ibid.* **206**, 1075 (1979); J. L. Barker and E. Anders, *Geochim. Cosmochim. Acta* **32**, 627 (1968).
4. U. Krähenbühl, J. W. Morgan, R. Ganapathy, E. Anders, *Geochim. Cosmochim. Acta* **37**, 1353 (1973); A. G. W. Cameron, *Space Sci. Rev.* **15**, 121 (1973); B. Mason, *Handbook of Elemental Abundances in Meteorites* (Gordon & Breach, New York, 1971).
5. I have included only reliable neutron activation data for this compilation. For example, the Pd content of BCR-1 by other methods is given as less than 4 ppb, in contrast to $\leq$ 0.03 ppb by neutron activation. Although the Pt content of BCR-1 is given as less than 10 ppb, I believe the actual value is several orders of magnitude lower than this. Neutron activation data were taken from: R. R. Keays, R. Ganapathy, J. C. Laul, U. Krähenbühl, J. W. Morgan, *Anal. Chim. Acta* **72**, 1 (1974); R. Wolf, G. R. Richter, A. B. Woodrow, E. Anders, *Geochim. Cosmochim. Acta* **44**, 711 (1980).
6. J. W. Morgan and G. A. Wandless, *Lunar Planet. Sci.* **10**, 855 (1979).
7. J. H. Crocket, in *Proceedings of the N.A.T.O. Advanced Study Institute—Activation Analysis in Geochemistry and Cosmochemistry* (Universitetsforlaget, Oslo, 1971), pp. 339-351.
8. R. Ganapathy, unpublished work.
9. F. Asaro, presented at the American Chemical Society Meeting, Houston, Texas, 25 March 1980 (reported to me by H. Kaufman and M. Rowe).
10. J. W. Morgan, personal communication.
11. _____, unpublished data [cited by K. Kimura, R. S. Lewis, E. Anders, *Geochim. Cosmochim. Acta* **38**, 683 (1974)].
12. K. Rankama and T. G. Sahama, *Geochemistry* (Univ. of Chicago Press, Chicago, 6th impression, 1968).
13. By measuring the activity ratio of ^{185}Os to ^{191}Os in the fish clay and terrestrial Os samples, one can establish whether $^{184}Os/^{190}Os$ in the fish clay is different from the solar system value. It was shown earlier that this ratio in terrestrial and meteoritic Os is the same within 2 percent [L. Grossman and R. Ganapathy, *Eos* **57**, 278 (1976)]. A value of -0.1 ± 0.4 percent was reported by H. Takahashi, H. Higuchi, J. Gros, J. W. Morgan, and E. Anders [*Proc. Natl. Acad. Sci. U.S.A.* **73**, 4253 (1976)].
14. J. W. Arden, *Nature (London)* **269**, 788 (1977).
15. It should be pointed out that a much more sensitive test for supernova debris would be to measure "live" ^{129}I (half-life, 17 million years) in this sample. There exist very sensitive methods to detect low amounts of ^{129}I through a combination of neutron activation and mass spectrometry [R. V. Ballad, D. W. Holman, E. W. Hennecke, J. E. Johnson, O. K. Manuel, L. M. Nicholson, *Health Phys.* **30**, 345 (1976)].
16. A density of 3 g/cm^3 was used for the calculation.
17. H. Stommel and E. Stommel, *Sci. Am.* **240**, 176 (June 1979).
18. The following three important papers on this subject have been published since this manuscript was submitted after revision: J. Smit and J. Hertogen, *Nature (London)* **285**, 198 (1980); L. W. Alvarez, W. Alvarez, F. Asaro, H. V. Michel, *Science* **208**, 1095 (1980); A. J. Naldrett and J. M. Duke, *ibid.*, p. 1417.
19. Ruthenium was determined only in sample 1 and toward the end of this investigation, to check whether the meteoritic pattern seen in other elements holds for Ru also. The Ru content was calculated through the ^{97}Ru and ^{103}Ru isotopes. Since ^{97}Ru had appreciably decayed, a value of 37 ± 28 ppb was obtained. Ruthenium-103 is produced from Ru as well as from U in the sample. The U content was 1 ppm. Applying a correction for the fission contribution ($174 \pm 8 - 135 \pm 14$), a value of 39 ppb for Ru was obtained.
20. I thank a number of individuals who contributed to the successful completion of this work: S. Gartner for the prompt dispatch of samples and for stimulating conversation; A. Meyer and coworkers at the University of Missouri-Columbia reactor for their efficiency and enthusiasm; J. Harris, J. Horvath, J. Bayda, and J. Volkert at J. T. Baker Chemical Company for assistance; H. Kaufman, T. Hurley, and A. J. Barnard for encouragement; J. Larimer and S. Larimer for many hours of conversation on the terminal Cretaceous Period; and J. W. Morgan for many helpful suggestions.

4 April 1980; revised 27 May 1980

Sulfur Dioxide Emissions from La Soufriere Volcano, St. Vincent, West Indies

Abstract. *During the steady-state period of activity of La Soufriere Volcano in 1979, the mass emissions of sulfur dioxide into the troposphere amounted to a mean value of 339 ± 126 metric tons per day. This value is similar to the sulfur dioxide emissions of other Central American volcanoes but less than those measured at Mount Etna, an exceptionally strong volcanic source of sulfur dioxide.*

The eruption of La Soufriere Volcano on the island of St. Vincent during April and May 1979 consisted of at least seven major events, which provided spectacular injections of volcanic material into the stratosphere (*1*). The heights for some of these injected clouds of ash were in excess of 18 km (*2*). The eruptions provided another opportunity to assess the importance of volcanic activity in the Western Hemisphere with respect to the loading of tropospheric SO_2.

During the latter stages of the eruption, a team from the Canadian Atmospheric Environment Service was sent to St. Vincent, and profiling of the SO_2 emissions was carried out over the first week in May 1979. The profiling was accomplished by means of boat transects of the volcanic plume (pathlength about 9 km) between Chateaubelair Island and Devolet Point off the west coast of St. Vincent (Fig. 1). A Barringer correlation spectrometer (COSPEC) was used in a vertically pointing mode to measure the total overhead burden of SO_2 along the transect. Since the COSPEC is an integrating remote sensor, it measures not the concentration of SO_2 per se but rather the burden, or the product of the concentration and the pathlength (in parts per million-meters), of all overhead SO_2. In other words, the COSPEC would measure the same signal if the total concentration of SO_2 were compressed into a 1-m layer and its concentration were measured in parts per million (volume to volume). Use of the COSPEC for estimating volcanic emissions of SO_2 is becoming standard (*3-5*), and this technique provides reliable volcanic SO_2 mass fluxes with a minimum of risk to the researcher.

The results of transects of the plume on 4 May 1979 are shown in Fig. 2. The COSPEC signal (calibrated from internal SO_2 cells) is plotted on the vertical axis, and the horizontal axis shows the crosswind distance from the Eulerian average center of gravity of the plume. The profiles in Fig. 2 are displayed in the orthogonal plane to the plume axis. The Eulerian average is a ground-referenced ensemble average of the measurements taken during a day. During this study, the ash loading in the steady-state plume from La Soufriere was not of a level to significantly deplete the incoming solar radiation (as indicated by the instrumental automatic gain control). On the basis of past experience with industrial plumes, we estimate that the SO_2 burden from this plume was well within the linear region of COSPEC response. Table 1 gives the plume dispersion results in terms of plume bearing and spread at the

0036-8075/80/0822-0923$00.50/0

Table 1. Results of the COSPEC measurements; EA, Eulerian average.

Time	Bearing from true north	Sigma Y* (m)	Area (10^5 ppm-m²)
	1 May 1979		
1030	282.9	2507	1.37
1112	277.7	2431	1.37
1353	271.1	1971	1.23
1427	266.4	2180	1.80
EA	273.6	2336	1.51
	3 May 1979		
1105	273.2	936	0.54
1130	295.2	1712	1.43
1314	290.3	718	2.14
1453	288.5	775	2.12
1533	288.4	981	2.46
EA	290.1	851	1.64
	4 May 1979		
1037	279.9	772	1.36
1212	299.6	1044	2.74
1230	285.0	1318	3.16
1356	285.6	830	2.09
EA	289.3	1081	2.30

*Plume width.

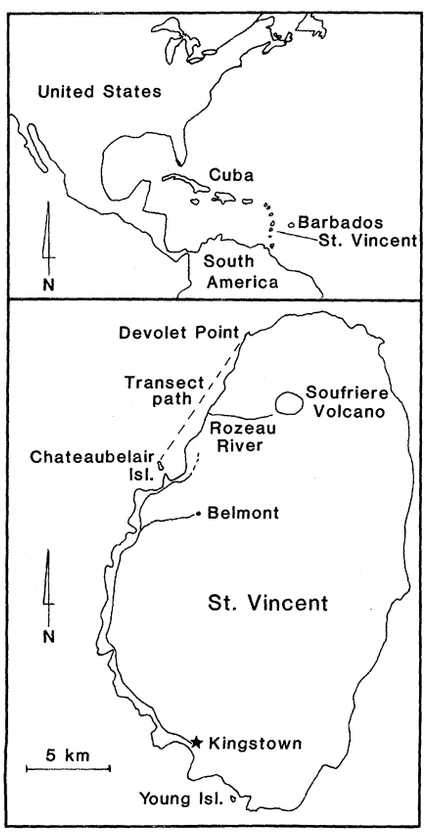
downwind distance of approximately 4.5 km from the center of original crater lake. The column designated "Area" in Tables 1 and 2 is the integrated concentration-pathlength product under the curves shown in Fig. 2.

To obtain a mass flux of SO_2 it is necessary to multiply the area in Table 1 by the mean wind speed advecting the plume and to convert from parts per million to mass units. Wind speeds were obtained from the meteorological office at the Arnos Vale Airport in St. Vincent, from the Barbados radiosonde station, and from visual observation of the time-of-flight motion of clouds passing the volcanic peak. These estimates of mean wind through the volcanic plume were combined to yield the values shown in Table 2. The estimated errors included with these values reflect the disparity in plume speed estimates obtained from the above sources and do not represent the error in the wind in a true root-mean-square (r.m.s) sense. Past experience with industrial sources has shown that the predominant error in calculating mass flux emissions with the COSPEC is due to uncertainties in the mean wind speed through the plume (*6*). Since the r.m.s. mean error of the average mass fluxes in Table 2 in general is larger than that due to the experimental uncertainties, we believe that the uncertainty in the total mass flux value of 339 metric tons per day is due to the variability of the source itself rather than to the measurement technique.

The mean value obtained in this study is comparable to the figure of 100 to 400 metric tons per day obtained by Stoiber and Jepsen (*4*) for Central American volcanoes. It is, however, smaller by a factor of 10 than the results obtained at periods of eruptive activity at Mount Etna (*5*), which appears to be the leading producer of tropospheric volcanic SO_2 monitored to date. The impact of SO_2 budgets in the analysis of problems of long-range transport of sulfur compounds is sometimes clouded by uncertainties about the importance of volcanic input. The results reported here should emphasize the care that is needed in extrapolating results obtained from a single volcano, such as Mount Etna, to worldwide volcanic SO_2 budgets.

Table 2. Mass fluxes of SO_2. The associated uncertainties in the mass fluxes are due to the variance in the wind plus an estimated 10 percent variance in the calculated COSPEC area. The error shown for each average mass flux is the standard deviation of the mean; Av., average; M., mean.

Time	Area (10^5 ppm-m²)	Mean wind ± error (m/sec)	Mass flux (metric ton/day)
		1 May 1979	
1030	1.37	8.2 ± 3.0	278 ± 105
1112	1.37	8.2 ± 3.0	278 ± 105
1353	1.23	9.0 ± 1.3	274 ± 48
1427	1.80	9.0 ± 1.3	400 ± 70
Av.			308 ± 62
		3 May 1979	
1105	0.54	7.2 ± 2.0	96 ± 28
1130	1.43	7.2 ± 2.0	254 ± 75
1314	2.14	8.7 ± 1.0	460 ± 70
1453	2.12	8.7 ± 1.0	456 ± 69
1533	2.46	8.7 ± 1.0	529 ± 81
Av.			359 ± 179
		4 May 1979	
1037	1.36	6.1 ± 1.0	205 ± 39
1212	2.74	6.1 ± 1.0	413 ± 79
1230	3.16	6.1 ± 1.0	476 ± 91
1356	2.09	5.7 ± 1.0	294 ± 59
Av.			347 ± 121
M.			339 ± 126



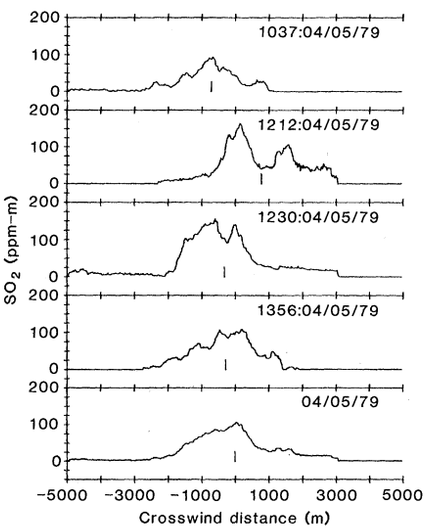


Fig. 1 (left). Map of St. Vincent, showing the COSPEC transect path. Fig. 2 (above). Data from four COSPEC SO_2 transects of the La Soufriere Volcano plume and the Eulerian composite (bottom curve). The crosswind distance is relative to the plume center of gravity (Table 1).

R. M. Hoff
A. J. Gallant
Atmospheric Dispersion Division, Air Quality and Inter-Environmental Research Branch, Atmospheric Environment Service, Downsview, Ontario, Canada M3H 5T4

References

1. J. B. Shepherd *et al.*, *Nature (London)* **282**, 24 (1979).
2. A. F. Krueger and H. R. LaPorte, paper M20 presented at the fall meeting of the American Geophysical Union, San Francisco, 2 to 7 December 1979; W. H. Fuller, Jr., W. H. Hunt, M. P. McCormick, S. Sokol, T. J. Pepin, paper M26 presented at the fall meeting of the American Geophysical Union, San Francisco, 2 to 7 December 1979.
3. A. J. Moffat, T. Kakara, T. Akimoto, L. Langan, *Air Note* (Environmental Measurements, Inc., San Francisco, 1972).
4. R. E. Stoiber and A. Jepsen, *Science* **182**, 577 (1973).
5. R. Haulet, P. Zettwoog, J. C. Sabroux, *Nature (London)* **268**, 715 (1977); L. I. Malinconico, Jr., *ibid.* **278**, 43 (1979).
6. R. M. Hoff, M. M. Millan, A. J. Gallant, *Alberta Oil Sands Environmental Winter Study, March 1976* (Alberta Oil Sands Environmental Research Project, Edmonton, 1977).

11 December 1979; revised 11 February 1980