

Chicxulub Crater, Yucatan: Tektites, impact glasses, and the geochemistry of target rocks and breccias

Christian Koeberl

Institute of Geochemistry, University of Vienna, A-1010 Vienna, Austria

ABSTRACT

A comparison of breccias and basement rocks from four drill holes near the Chicxulub impact structure, Yucatan (a possible Cretaceous-Tertiary [K-T] boundary crater), with black and yellow impact glasses from the Haitian K-T boundary layer shows that mixtures of andesite-like rocks with carbonates and evaporites from Chicxulub are compositionally different from the yellow glasses. At the time of impact, the Chicxulub area was covered by evaporitic and carbonate deposits several kilometres thick. Because impact glasses are generally produced by shock melting of surface rocks, a link between the Haitian glasses and Chicxulub is difficult to understand. The $\delta^{34}\text{S}$ isotopic signature of Chicxulub breccias and evaporites is incompatible with that of a continental K-T boundary. We suggest that the pre-impact target stratigraphy at Chicxulub as well as the interpretation of the carbonate-evaporite rocks as breccias should be revised.

INTRODUCTION

Abundant evidence exists for at least one large impact on or near the North American continent at 65 Ma, the Cretaceous-Tertiary (K-T) boundary. For example, impact glasses were discovered at a K-T section in Haiti (Izett et al., 1990; Sigurdsson et al., 1991a). The question regarding the source crater is important: the radiometric age of the Manson crater, Iowa, is indistinguishable from that of the K-T boundary (e.g., Hartung et al., 1990), and the Chicxulub structure in Yucatan, Mexico, was also proposed as a K-T impact crater (Hildebrand et al., 1991). Geophysical studies and stratigraphic data from exploration drill holes (e.g., Hildebrand et al., 1991) strengthened the interpretation that Chicxulub is an impact crater. Shock-metamorphic effects were found recently within different breccias from inside the structure, and isotopic and paleomagnetic data indicate that the Chicxulub impact event occurred at or near the K-T boundary (Sharpton et al., 1992). We compare the compositions of rocks from Chicxulub with those of the impact glasses found at the Haitian K-T boundary.

SAMPLES AND RESULTS

Samples were taken from four different drill holes between 1.3 and 2 crater radii from the center of the Chicxulub structure (Fig. 1), representing the continuous ejecta deposits of the impact as well as target rocks. Samples Y1-N42 and Y1-N43 are sandstones overlying the crystalline basement; Y2-N6 and Y2-N9 are breccias consisting of carbonates, dolomitic limestones, and anhydrite; Y4-N31 is a sandstone overlying the basement;

Y4-N36 is a fine-grained metaquartzite, probably part of the basement; and Y5A-N11 is an evaporite. The mineralogy of the two Y2 breccias as determined by X-ray diffraction is: Y2-N6—gypsum, anhydrite, dolomite, and calcite; and Y2-N9—anhydrite, dolomite, and calcite.

Results of the analyses of the Chicxulub rocks are given in Table 1. According to Hildebrand et al. (1991) and Pope et al. (1991), the breccias are from a proximal ejecta deposit, and are therefore representative of the target rocks. The trace element contents of the two Y2 breccia samples are compatible with their origin in a shallow-water, evaporitic environment. The evaporite Y5A-N11, which is from a different stratigraphic position, has almost identical elemental contents, showing that the chemical composition of the target rocks varies only slightly.

IMPACT GLASSES FROM HAITI

Black and yellow impact glasses with compositions similar to the upper continental crust were found in the K-T boundary layer on Haiti (Izett et al., 1991; Izett, 1991; Sigurdsson et al., 1991a, 1991b; Koeberl and Sigurdsson, 1992). The yellow glass is rich in Ca (20%), Sr, and S (0.6%), which was suggested to result from a carbonate and/or anhydrite contribution (Izett, 1991; Sigurdsson et al., 1991b). The Rb-Sr and Sm-Nd isotopic signatures of the black glass are compatible with those of the continental crust (Sigurdsson et al., 1991a, 1991b; Premo and Izett, 1992).

Although the black glass was called andesitic or andesite like in composition (Sigurds-

son et al., 1991a), their rare earth element (REE) patterns and trace element contents do not agree with those of andesites (see, e.g., Table 1). The andesites have lower heavy REE concentrations by a factor of about two, a steeper slope, and usually no Eu anomaly (Koeberl and Sigurdsson, 1992). Other trace element concentrations and ratios (such as Co, Th/U, La/Th) do not support a derivation from rocks of a composition closely related to Mexican andesites. To compare the Chicxulub rocks with the Haitian impact glasses, we need to consider the nature and origin of tektites and impact glasses.

ORIGIN OF TEKTITES AND IMPACT GLASSES

Tektites are natural glasses, most of which are centimetre-sized spherical objects that have low water contents (~0.01 wt%), are relatively homogeneous chemically (on a 50–100 μm scale), and are found in four strewn fields on Earth: the North American, Moldavian, Ivory Coast, and Australasian. Tektites found within such fields are related by petrological, physical, and chemical properties as well as their age (e.g., Koeberl, 1986, 1992). Impact glasses, of which tektites are a subgroup, are the product of melting and quenching of terrestrial rocks during hypervelocity impact on the Earth. The chemistry of tektites is in many respects identical to the composition of upper crustal material (Koeberl, 1986), which is confirmed by Rb/Sr and Sm/Nd isotopic studies (e.g., Blum et al., 1992). Their composition always corresponds to that of the impact target rocks. The process by which tektites and

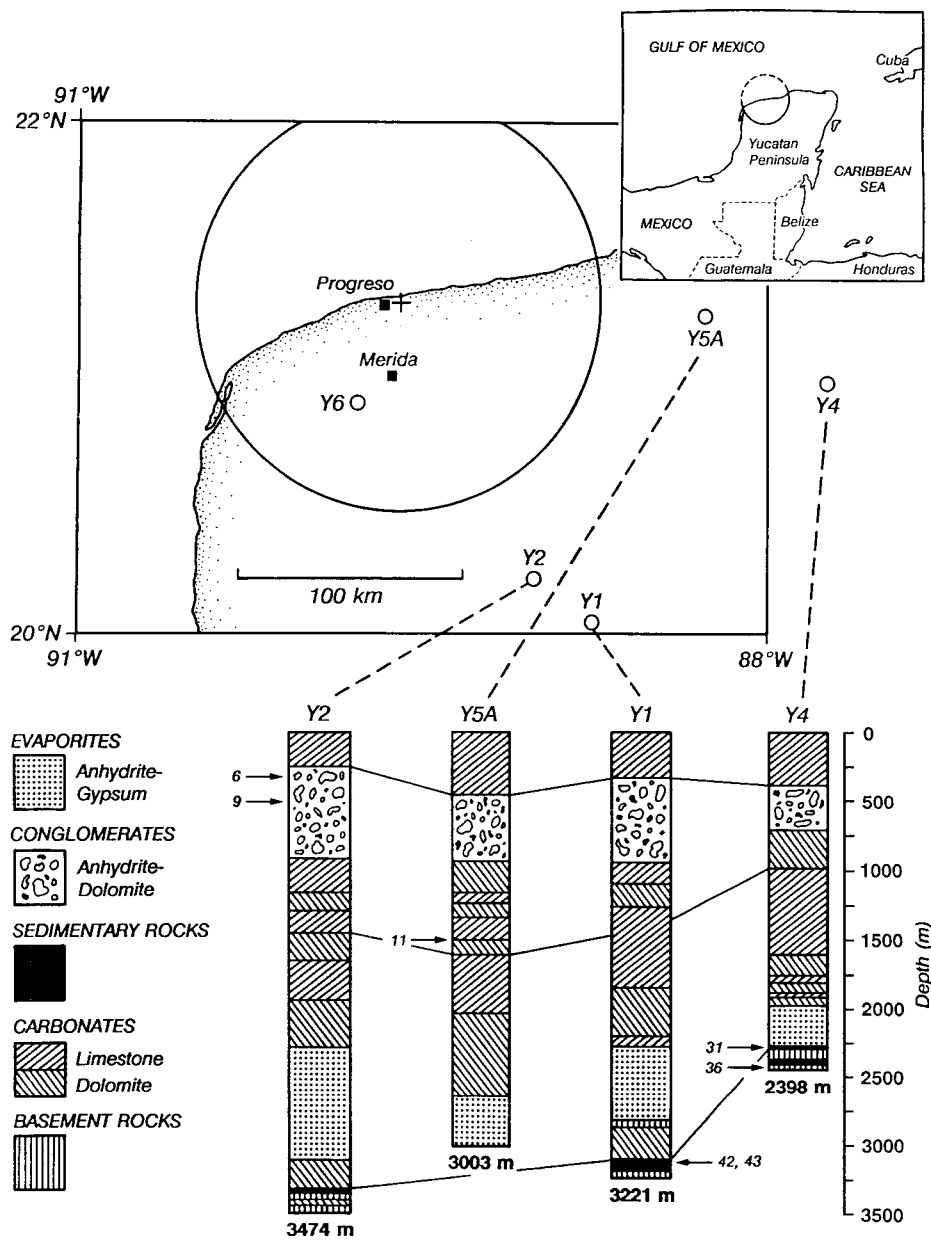


Figure 1. Location of drill holes in relation to Chicxulub structure. Inset shows general location of Chicxulub structure. Crater rim has been drawn according to outline of geophysical anomalies (Hildebrand et al., 1991). Lower part shows schematic stratigraphic columns of four drill holes and sample locations. Sample depths: Y2-N6, 301–303 m; Y2-N9, 500–503 m; Y5A-N11, 1510–1513 m; Y1-N42, 3083–3088 m; Y1-N43, 3097–3103 m; Y4-N31, 2298–2301 m; and Y4-N36, 2423–2525 m.

impact glasses are formed can be described as nonequilibrium shock melting of inhomogeneous target rocks. Tektite-producing events also produce large craters; e.g., the Australasian strewn field is ~100 km in diameter (Blum et al., 1992; Koeberl, 1992).

The study of cosmogenic radionuclides in tektites and impact glasses is of great importance for understanding tektite origin. The ¹⁰Be content of tektites can only have been introduced from sediments that have absorbed the ¹⁰Be produced in the terrestrial atmosphere (Pal et al., 1982). Raisbeck et al. (1988) found that Muong Nong-type tektites contain less ¹⁰Be than australites, showing that splash-form tektites were produced

from the uppermost layer of the target rocks, whereas Muong Nong types come from a deeper layer (for discussions, see Blum et al., 1992; Koeberl, 1992).

CHICXULUB ROCKS VS. HAITI GLASSES

The Haitian impact glasses must have an origin similar to that of normal impact glasses or tektites—i.e., formed by impact melting of target rocks that were at or near the surface at the time of the impact. The Chicxulub crater is now covered by a thick layer (several hundred metres at least) of Tertiary sedimentary rocks, mainly limestone. Underneath this cover is a sedimentary sequence

(3–6 km thick; mainly carbonates and evaporites) that overlies a metamorphic basement (Hildebrand et al., 1991). Impact into such rocks would release large quantities of CO₂ (Hildebrand et al., 1991) and SO₂ (Sigurdsson et al., 1992) into the atmosphere.

Hildebrand et al. (1991) hypothesized that the rocks in the Chicxulub area may have been the source for the Haitian impact glasses, and Sigurdsson et al. (1991a, 1991b) suggested that the rare yellow glasses were formed by the admixture of carbonates and evaporites to andesite-like rocks. With the data given in Table 1, we can evaluate this suggestion. The upper few kilometres of the pre-impact stratigraphy at Chicxulub, as known today (e.g., Hildebrand et al., 1991), do not seem to contain any andesite-like rocks. However, to evaluate the mixing argument, we assume that the black Haiti glasses represent the target-rock composition.

The Y2 breccia compositions were used for comparison because impact breccias are a representative mixture of the target lithology. Different mixtures of evaporite breccias (Table 1) and “andesite” (black glass) were calculated to reproduce the Ca content of the yellow glasses; the composition of these mixtures is then compared to that of the yellow glass. One argument for an evaporitic contribution is the high Ca and S content of the yellow glass. However, it is evident from the two examples given in Figure 2 that, if the Ca content is optimized, most of the other elements show no agreement at all. Koeberl and Sigurdsson (1992) found ~0.003 wt% S in the black glass; given the abundance of sulfur-bearing rocks at Chicxulub, such a low value seems unlikely for rocks that were formed from target rocks at Chicxulub.

All analyzed carbonates and evaporites have relatively low REE abundances (~0.5–5 × CI), flat REE patterns, low Th abundances, and Th/U ratios <1, among other characteristics. Such abundances, ratios, and patterns are typical for carbonates and evaporites, and the small variations between samples from different drill holes confirm that our samples are representative of most such rocks at Chicxulub. Mixtures of andesite-like rocks with a high proportion of carbonate and evaporite rocks—necessary for the high Ca, Mg, and S contents—yield compositions that disagree with most trace element abundances, ratios, and REE patterns. The REE patterns of the black and yellow Haiti glasses are very similar (Fig. 3). The only rock with similar high REE abundances is the metaquartzite (Y4-N36), for which other elemental abundances do not fit. In addition, most rocks show a pronounced Eu anomaly. Thus, a mixture of a rock having a composition similar to the black glass

TABLE 1. MAJOR AND TRACE ELEMENT COMPOSITION OF CHICXULUB CRATER ROCKS AND COMPARISON DATA FOR HAITI IMPACT GLASSES

	Y1-N42 Sandstone Red	Y1-N43 Gray	Y2-N6 Breccia	Y2-N9 Breccia	Y4-N31 Red Sandst.	Y4-N36 Meta- quartzite	Y5A-N11 Evaporite	Andesite (Pico Orizaba)	Haiti Black Glass	Haiti Yellow Glass
SiO ₂	89.0	97.0	1.0	0.4	80.0	91.0	0.2	61.2	63.29	48.73
TiO ₂	0.19	0.049	0.035	0.015	0.18	0.27	0.024	0.65	0.68	0.64
Al ₂ O ₃	4.71	0.28	1.2	0.29	3.05	1.92	0.47	17.1	15.33	13.25
FeO	1.51	0.10	0.57	0.20	2.16	2.18	0.37	4.33	5.27	4.98
MgO	0.52	0.079	8.52	9.34	2.57	0.65	11.57	2.6	2.55	4.02
CaO	0.20	0.24	36.10	37.46	3.63	1.11	35.14	5.20	7.21	24.71
Na ₂ O	0.270	0.058	0.594	0.149	0.203	0.031	0.216	4.65	3.72	2.54
K ₂ O	1.70	0.11	0.46	0.19	1.21	0.31	0.53	2.00	1.62	0.85
P ₂ O ₅	0.068	0.029	0.36	0.38	0.175	0.17	0.38	n.d.	0.07	0.06
SO ₃	0.057	0.30	26.22	24.97	0.12	0.042	24.29	n.d.	0.004	0.55
CO ₂	0.27	0.46	20.81	24.32	6.56	0.40	26.98	n.d.	<0.01	<0.01
Total	98.49	98.71	95.82	97.71	99.85	98.09	100.18	97.73	99.74	100.13
Sc	4.74	0.66	1.37	0.48	4.61	2.13	0.96		20.6	21.3
Cr	27.8	23.3	3.4	1.9	28.1	23.4	3.1	27	27.4	29.7
Mn	39	15	77	54	534	170	55	620	1310	1150
Co	2.52	0.53	1.89	0.43	9.89	3.62	0.36	5	14.8	22.7
Ni	5	3	15	15	10	15	15	14	22	285
Zn	51	<2	5	1	5	<3	3		27.1	74.3
Ga	4.5	0.4	1.5	0.6	4.9	5	1		11.8	6.5
As	0.78	0.67	0.36	0.51	2.36	4.26	3.95		0.13	0.65
Se	0.2	0.1	0.1	0.04	<0.3	<0.4	0.1		0.00	2.63
Br	3.51	0.39	1.23	1.14	2.99	0.51	1.17		0.12	1.40
Rb	88.3	3.72	5.15	2.97	42.9	13.2	3.18	44	59.2	25.6
Sr	100	95	3280	2690	125	<30	1020	501	401	704
Zr	460	250	20	15	450	670	50	162	166	199
Ag	0.1	0.04	0.06	0.08	0.04	<0.1	0.05		<1	<3
Sb	0.66	0.19	0.02	0.059	0.24	0.34	0.19		0.28	2.56
Cs	4.79	0.39	0.18	0.076	3.05	0.25	0.097	1.34	1.57	2.43
Ba	50	180	30	15	55	40	20	640	503	974
La	22.4	15.7	2.63	0.78	22.3	31.6	0.72	17.8	22.4	17.8
Ce	43.3	26.6	4.91	1.33	45.9	57.9	2.08		46.3	35.8
Nd	20.3	11.8	3.2	1.05	21.8	27.2	1.8		24.4	19.9
Sm	3.43	2.01	0.73	0.25	4.98	6.67	0.55		5.23	4.12
Eu	0.66	0.42	0.15	0.037	1.09	1.44	0.036	1.17	1.52	1.17
Gd	3.7	1.3	<0.5	<0.3	4.6	6.4	<0.4		5.11	4.28
Tb	0.64	0.22	0.068	0.021	0.77	1.15	0.041	0.44	0.89	0.78
Dy	3.4	1.3	0.4	<0.2	4.2	6.4	0.2		5.39	4.78
Tm	0.26	0.11	<0.05	<0.05	0.31	0.52	<0.03		0.47	0.46
Yb	1.71	0.65	0.23	0.081	1.96	3.31	0.075		3.20	2.78
Lu	0.26	0.097	0.035	0.019	0.31	0.47	0.016		0.45	0.36
Hf	13.2	6.78	0.29	0.14	12.1	18.8	0.34	4.01	4.06	3.23
Ta	0.46	0.17	0.04	0.022	0.42	0.56	0.024	0.47	0.33	0.66
W	0.6	1.6	0.9	0.7	0.8	1.1	0.8		0.99	1.43
Ir (ppb)	<0.6	<0.5	<1	0.3	<1	0.4	<0.5		<2	2.00
Au (ppb)	0.2	2	0.4	0.2	0.8	1.5	0.2		1.80	11.5
Hg	<0.1	0.02	<0.1	<0.08	<0.3	<0.18	0.11		<1	<1
Th	5.39	1.83	0.44	0.23	5.28	8.81	0.51	4.07	6.36	5.08
U	1.27	0.74	0.74	2.05	1.66	2.91	3.83	1.51	1.10	1.24

Note: Major element data in wt%, trace element data in ppm (except as indicated); for analytical methods see Koeberl (1992) and Koeberl and Sigurdsson (1992); Pico de Orizaba andesite data from Robin (1982); Haiti black and yellow glass data from Koeberl and Sigurdsson (1992); n.d.—not determined.

with evaporites, as proposed by Sigurdsson et al. (1991b), yields different REE patterns as well as REE abundances that are far lower than those of the yellow glasses. The same conclusion—that evaporites were not involved in the production of the yellow glasses—was reached independently by Blum

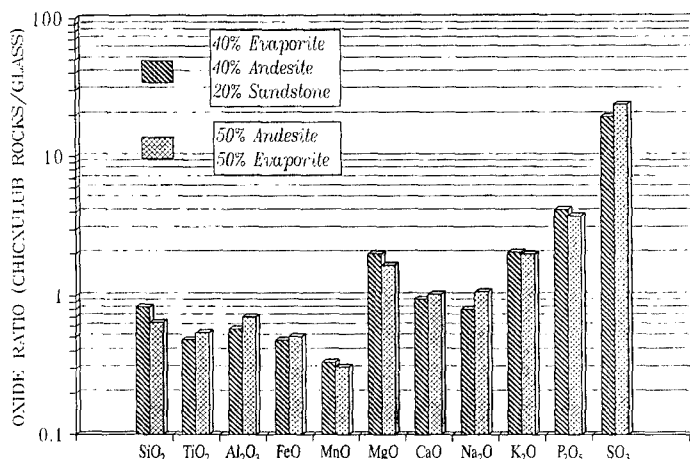


Figure 2. Major element composition of mixtures of Chicxulub country rocks (recalculated from data in Table 1; volatile free) compared with Haitian yellow impact glass. Admixture of rocks yielding sufficient Ca contents do not provide any fit for other elements.

and Chamberlain (1992) from oxygen isotope studies.

SULFUR AND BORON ISOTOPES

We measured $\delta^{34}\text{S}$ in three Chicxulub rocks, with the following results: breccia Y2-N6, +17.6‰; breccia Y2-N9, +17.5‰; and evaporite Y5A-N11, +16.0‰. These are fairly typical values for marine sulfate minerals (e.g., Faure, 1986), and are not very different from the value of +13.2‰ given by Sigurdsson et al. (1991b) for the Haiti yellow glass. Perry et al. (1992) predicted, on the basis of the fact that an impact into evaporites would release enormous amounts of sulfur into the atmosphere, that if impact sulfur is volatilized from the Chicxulub site with little isotopic fractionation, a ^{34}S enrichment may occur in terrestrial K-T boundary layers. We therefore measured samples from the Raton basin–Starkville South K-T boundary section, which yielded a $\delta^{34}\text{S}$ of +2.4‰ ± 0.2‰. We conclude that either Chicxulub did not contribute significantly to the central United States K-T boundary sections or some (unexpected) isotope fractionation took place.

The boron isotope analyses allow other interesting comparisons. The $\delta^{11}\text{B}$ of the yellow Haiti glass is -2.1‰ (Sigurdsson et al., 1991b), similar to normal sedimentary rocks. However, evaporitic rocks are known to have very high $\delta^{11}\text{B}$ values (+20‰ to +60‰) because of the marine signature (e.g., Vengosh et al., 1992). Although the ^{34}S composition of the yellow glass may be consistent with an evaporitic source, the boron isotopic composition may not be, which presents a conflict.

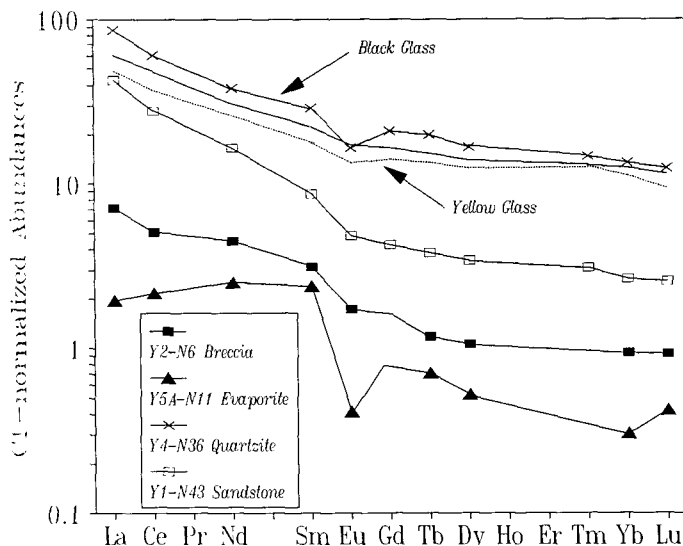


Figure 3. Chondrite-normalized rare earth element (REE) patterns for Chicxulub country rocks compared with black and yellow impact glasses from Haiti. Admixtures of carbonates and evaporites to andesitic rocks (similar to black glass) yield REE patterns and abundances different from ones observed for yellow glass.

CONCLUSIONS

We studied the suggestion that the Haitian impact glasses were formed from Chicxulub rocks, in particular that the yellow glass was formed by mixing of andesite-like rocks (which can be assumed to have a composition similar to that of the black glasses) with evaporites (Sigurdsson et al., 1991b, 1992). Tektites (and impact glasses) are formed from the surface layer of target rocks. However, current knowledge indicates that there were no silica-rich rocks on or near the surface at the time of the Chicxulub impact; the target rocks were supposedly dominated by carbonates and evaporites several kilometres thick (Hildebrand et al., 1991). Sharpton et al. (1992) reported the presence of some granitic gneiss basement clasts from breccias within the Chicxulub structure, but no information about their pre-impact stratigraphic position is available. Our analyses show that the composition of any mixtures involving evaporitic rocks is incompatible with the chemistry of the yellow glasses. The same conclusion was obtained independently by Blum and Chamberlain (1992) from oxygen isotope studies. Our analyses provide three immediate conclusions: (1) evaporitic rocks were not involved in the formation of the Haitian yellow glasses; (2) the pre-impact stratigraphy at Chicxulub, as interpreted today, needs revision to allow for the presence of silica-rich rocks near the surface; and (3) the interpretation of the Y2 breccias as impact breccias may be wrong.

Shoemaker and Izett (1992) have found evidence for two different impact layers at North American K-T boundary sites and have proposed that at least two impacts might be responsible for the K-T event. Whereas the composition of the Haitian black glasses is compatible with that of some impact glasses from the Manson crater (Koeberl and Hartung, 1992), more detailed chemical and isotopic studies (Premo and Izett, 1992) will be necessary. No direct conclusions regarding a contribution from the Manson crater can be drawn from our analyses. However, the Manson crater may be too small to explain the events at the K-T boundary, although Anderson and Hartung (1992) have argued otherwise.

We conclude, on the basis of the data currently available, that there are still questions regarding Chicxulub as the source for the Haitian K-T boundary glasses. The suggestion that the Chicxulub event was of such large dimensions that our current knowledge of crater and tektite formation is turned upside down resembles a convenient *deus ex machina* solution.

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Reviewer's comment

A significant contribution to the rapidly expanding literature on the events that occurred at the K/T boundary.

Raymond Anderson