Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico

SPECIAL REPORT

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ABSTRACT

We suggest that a buried 180-km-diameter circular structure on the Yucatán Peninsula, Mexico, is an impact crater. Its size and shape are revealed by magnetic and gravity-field anomalies, as well as by oil wells drilled inside and near the structure. The stratigraphy of the crater includes a sequence of andesitic igneous rocks and glass interbedded with, and overlain by, breccias that contain evidence of shock metamorphism. The andesitic rocks have chemical and isotopic compositions similar to those of tektites found in Cretaceous/Tertiary (K/T) ejecta. A 90-m-thick K/T boundary breccia, also containing evidence of shock metamorphism, is present 50 km outside the crater's edge. This breccia probably represents the crater's ejecta blanket. The age of the crater is not precisely known, but a K/T boundary age is indicated. Because the crater is in a thick carbonate sequence, shock-produced CO_2 from the impact may have caused a severe greenhouse warming.

INTRODUCTION

The debate concerning the postulated impact at the Cretaceous/Tertiary (K/T) boundary (Alvarez et al., 1980) may be resolved by the discovery of the impact site and/or the thick proximal deposits of the impact (Hildebrand and Boynton, 1990a, 1990b). An ~50-cm-thick K/T boundary ejecta layer in Haiti and proximal impact-wave deposits in the Caribbean region suggest that the K/T boundary impact occurred between North and South America. Circular anomalies, ~200 km in diameter, in both magnetic and gravity fields (with associated andesitic rocks) on the northwestern margin of the Yucatán peninsula of México (Fig. 1) have been interpreted as representing a volcanic center (Lopez Ramos, 1975) or an impact crater with associated extrusive material (Penfield and Camargo, 1981). We describe geophysical, stratigraphic, and petrologic evidence indicating that this structure is a large impact crater of possible K/T boundary age.

GRAVITY AND MAGNETIC DATA

The circular structure is buried in the middle of the Yucatán carbonate platform in a region of subsequent tectonic quiescence. Bouguer gravity data show an ~180-km-diameter, circular, 30 mgal, negative anomaly (Fig. 2) similar in shape to those found over large impact craters (Fig. 3). A center 10 km east of Progreso, near the town of Chicxulub Puerto, best fits a 20 mgal central high (20 km radius) and two internal concentric lows (35 and 60 km radii); the margin of the anomaly might be best fit by a center slightly farther northeast. The gravity-field anomaly is truncated to the north by an east-northeast-trending lineament that crosses the Yucatán platform north of the present coastline. A negative anomaly trails ~100 km to the south from the circular anomaly. Its internal circular structure is disrupted near both the truncating lineament and the southward-extending trough.

Total magnetic-field data (Penfield and Camargo, 1981; Lopez Ramos, 1975) show ~210-km-diameter, circular, dipolar anomalies with large horizontal gradients and some concentric structure nearly coincident with the gravity anomaly. Large-amplitude, short-wavelength anomalies (up to ~1000 nT) occur over the central gravity high, but extend farther, to a radius of ~35 km. An outer zone of weaker (5 to 20 nT) short-wavelength anomalies extends to a radius of ~105 km, but has an irregular margin. The

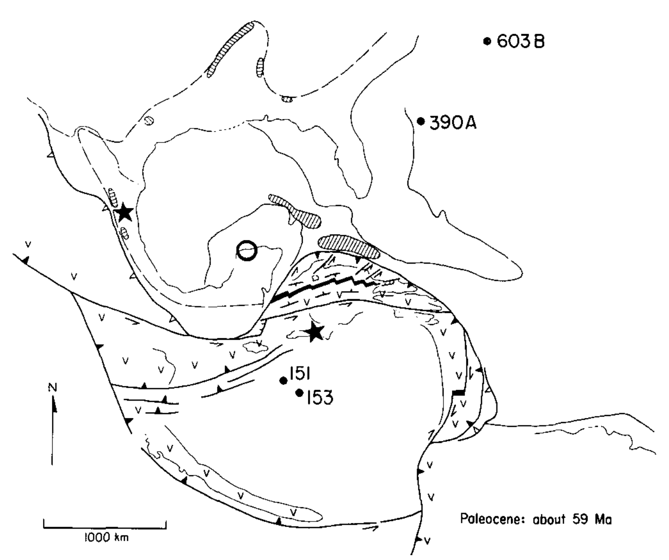

Figure 1. Plate tectonic reconstruction of Caribbean region near K/T time modified from Pindell and Barrett (1990). Bold lines—fault zones between plates; arrows and triangles indicate relative motions. Solid triangles—subduction zones; open triangles—thrusting. V pattern—subduction-related island-arc volcanism. Dashed line—paleoshoreline on North American continent. Diagonal-rule pattern—areas of possible impact-wave deposits. Dots—Deep Sea Drilling Project sites: impact-wave deposits are found at sites 151, 153, and 603B. Stars—positions of ~50-cm-thick K/T ejecta layers found at sites in Haiti and Mexico. Circle—Chicxulub crater on Yucatán platform.

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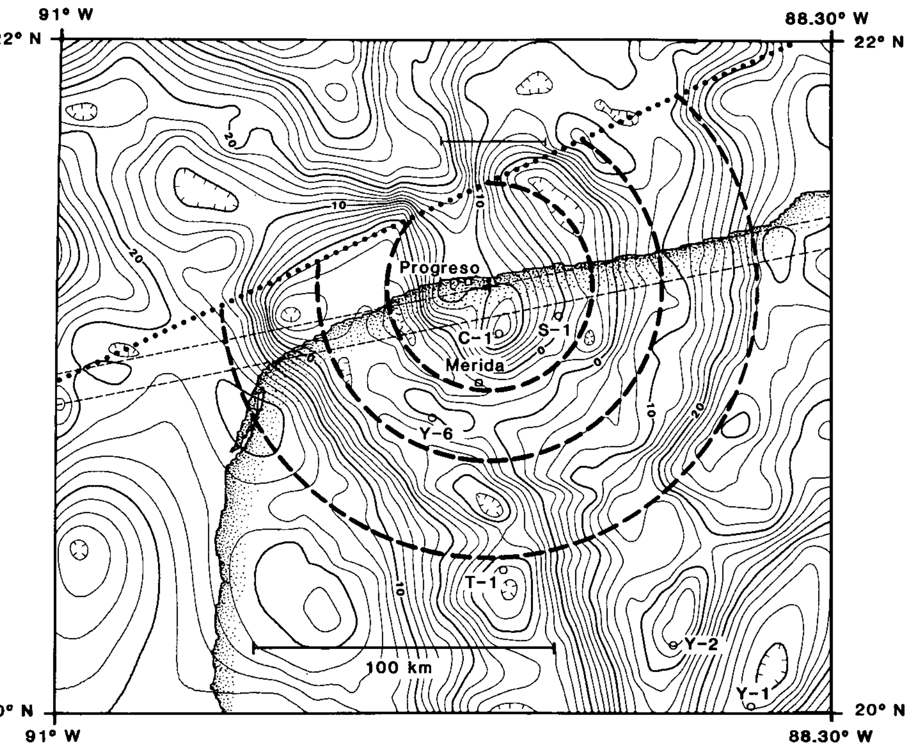

Figure 2. Contour plot (contour interval = 2 mgal) of Bouguer gravity data (Gravity Anomaly Map Committee, 1988) covering northwest corner of Yucatán Peninsula, Mexico. Outermost heavily dashed circle—margin of circular negative gravity anomaly; two other circles—concentric lows within negative anomaly; cross—center of anomaly. Dotted line—east-northeast-trending regional lineament that truncates anomaly. Two light dashed lines indicate positions of profiles shown in Figure 3. Dark solid line (top) shows approximate position of seismic reflection profile. Exploration wells drilled by Petróleos Mexicános: C-1 = Chicxulub-1; S-1 = Sacapuc-1; Y-1, Y-2, Y-6 = Yucatán-1, 2, and 6; T-1 = Ticul-1.

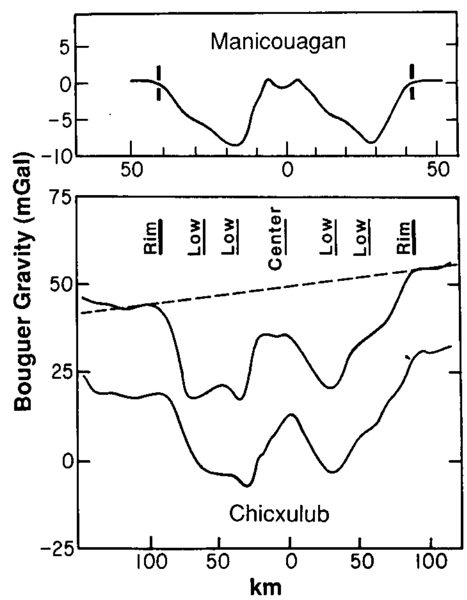

Figure 3. Two east-northeast Bouguer gravity profiles (parallel to coastline) across Chicxulub structure showing symmetrical negative anomaly with central high (see Fig. 2 for positions of profiles). Profiles are drawn through data points spaced at ~6 km intervals. Regional field decreases from east to west, as shown by dashed line. Bottom profile is located ~10 km south of upper (central) profile. Upper profile has been displaced 25 mgal above its true position to separate the two. Center of crater, two concentric gravity lows, and suggested crater rim are indicated along central profile. Profile from Manicouagan crater shown for comparison is from Sweeney (1978); regional background was removed. Vertical and horizontal scales on Manicouagan profile have been expanded for comparison purposes.

magnetic-field anomalies extend to the north without significant disruption across the lineament that truncates the gravity anomaly. The central anomalous zone is slightly elongated in a northwest-southeast direction. Modeling of the magnetic-field anomalies places the top of the magnetic source bodies at a depth of ~1100 m (Penfield and Camargo, 1981).

STRATIGRAPHY

The subsurface stratigraphy of the northern Yucatán peninsula is known primarily from petroleum exploration drillholes (Murray and Weidie, 1967; Lopez Ramos, 1975, 1983; Marshall, 1974; A. E. Weidie, Jr., et al., unpublished cross section). A structurally uncomplicated platform sequence of nearly horizontal Lower Cretaceous to Quaternary carbonates and evaporites overlies a poorly known crystalline basement of probable Paleozoic age. In the northern part of the peninsula the platform sequence is at least 3500 m thick. Three deep exploration wells (1527 to 1631 m total depth) have been drilled within the margins of the geophysical anomalies (Fig. 2). The upper sequence ranges from Pleistocene to Paleocene in age and is a flat-lying, conformable sequence with no known significant stratigraphic breaks (Fig. 4). The sedimentary facies and fauna reported from these wells indicate a deeper-water environment than that found elsewhere on the platform. The rocks are fossiliferous limestones and marls with minor shale, bentonite, and chert. The unit underlying the Tertiary sequence is composed of fossiliferous limestone, marl, shale, and minor bentonite, and has been previously dated as Late Cretaceous.

The wells penetrated coarse breccias and clastic and andesitic igneous rocks at depth (Fig. 4). In wells C-1 and S-1, limestone and bentonite breccias (containing Cretaceous fossils), are interbedded with marlstone, shale, and sometimes-dolomitic limestones. Thin intercalations of andesitic glass are present in the lower part of this unit. Well Y-6 recorded sandstone interbedded with shale, marl, and bentonite at this level. Thick units of andesitic glass underlie the breccias in wells C-1 (with minor interbedded tuffs) and S-1. Well Y-6 intersected microcrystalline andesitic rock before bottoming in laminated anhydrite. Well C-1 also intersected microcrystalline andesitic rocks below the andesitic glass unit.

These andesitic igneous rocks occur only inside the circular zone of the geophysical anomalies; several other nearby drillholes (Fig. 2) have not encountered these rocks. Possible analogues to the limestone and bentonitic breccias compose the uppermost Cretaceous stratigraphy in other holes. For example, the Yucatán-2 (Y-2) well, located 135 km southeast of the center of the anomalies (Fig. 2), intersected a unit of bentonitic limestone breccia from 240 to 330 m.

PETROLOGY

To investigate the origin of the andesitic igneous rocks and carbonate breccias within the area of the circular anomalies, we studied some of the few remaining samples from petroleum exploration using optical microscopy, X-ray diffraction (XRD), and electron-microprobe techniques (Kring et al., 1991).

Sample Y6 N14 (Fig. 5A) came from a depth of 1208 to 1211 m in the Y-6 well (Fig. 4), from a predominantly sandstone unit. However, this sample is a partly chloritized, polymict breccia with angular to subrounded igneous and sedimentary clasts in a fine-grained calcite matrix (~25%). The sedimentary clasts (~5%) are anhydrite and carbonate rocks; there are also trace amounts of small polycrystalline quartz clasts. The igneous clasts (~65%) are dominated by a microcrystalline groundmass consisting of alkali feldspars ($Ab_{93}Or_2An_5$ to $Ab_{14}Or_{85}An_1$), plagioclase feldspars ($An_{13}Ab_{84}Or_3$), and augite ($Wo_{50}En_{39}Fs_{11}$). About half of the igneous clasts contain lithic inclusions and/or ropy-

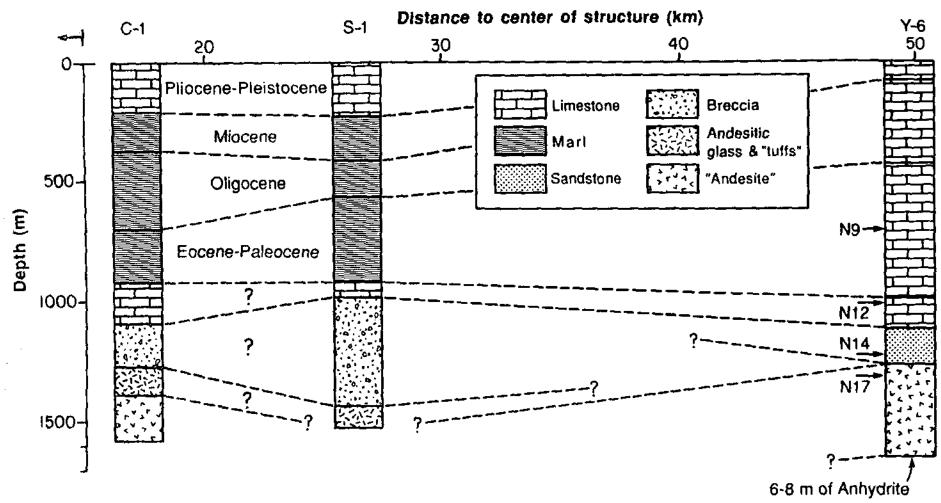

Figure 4. Stratigraphic columns from three deep interior wells in Chicxulub crater (see Fig. 2). Vertical exaggeration ×10. Drillholes are spaced according to their distance from estimated center of structure. Arrows show locations of samples from well Y-6, together with sample numbers. Ages have not been given to units at base of drilled section; these units have previously been regarded as Upper Cretaceous.

TABLE 1. COMPOSITION OF CHICXULUB MELT ROCKS AND HAITIAN TEKTITES

Oxide	G6*	90G RANGE	11M*	BE*	N17
SiO_2	63.2	60.3-67.6	63.2	63.1 ±2.1	63.2 /60.5
TiO_2	0.72	0.7- 0.8	0.8	0.7 ±0.1	0.4 / 0.4
Al_2O_3	15.5	13.7-15.3	14.7	15.2 ±0.3	12.6 /13.6
CaO	7.9	4.7-10.9	7.1	7.3 ±1.7	10.2 /10.5
MgO	2.6	2.4- 3.8	2.8	2.7 ±0.3	3.1 / 3.2
FeO	5.4	4.7- 5.7	5.3	5.4 ±0.4	4.5 / 5.0
Cr_2O_3	0.01				
MnO	0.16	0.1- 0.2	0.2	0.14±0.06	0.1 / 0.1
NiO	0.01				
Na_2O	2.7	2.4- 3.6	3.3	3.6 ±0.3	4.0 / 4.7
K_2O	1.7	1.0- 1.8	1.5	1.6 ±0.1	1.9 / 1.9
P_2O_5	0.27				0.08/ 0.1
Total	100.17		98.8	99.74	100.08/100.09

Note: All analyses in weight percent. Sample G6: glass from Haitian ejecta layer residue (this work); 90G RANGE, 11M: Haitian glasses described by Izett et al. (1990); BE: average Haitian glass (1σ variation; Sigurdsson et al., 1991); N17: slightly-altered, andesitic, melt-rock sample from the Y-6 well, Chicxulub crater. All analyses by electron microprobe, except N17 which was analysed by X-ray fluorescence (reported on a sulfur-free basis). No numbers = not determined.
* Values given are averages of multiple analyses.

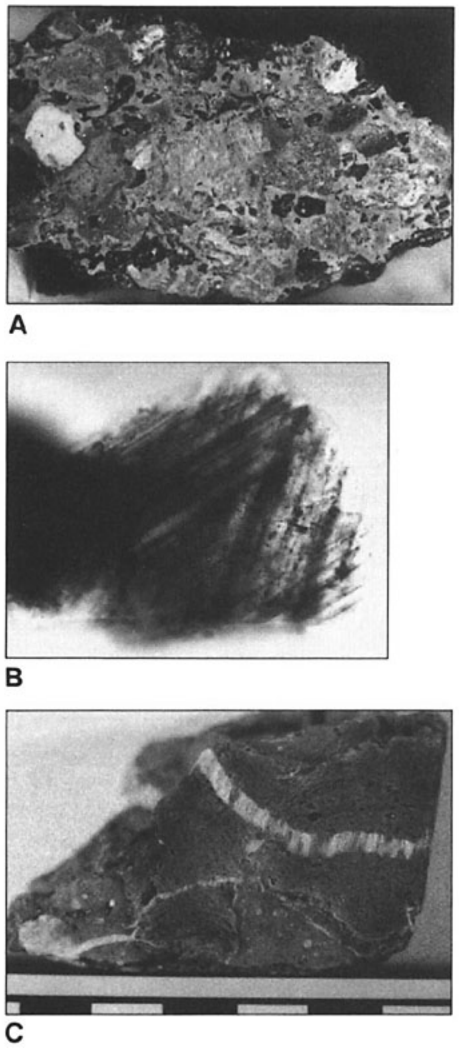

Figure 5. A: Polished slab showing polymict breccia sample Y6 N14. Specimen is 4 cm across. B: Shocked quartz grain (0.32 mm across) from polymict breccia Y6 N14. Grain shows eight sets of lamellae when rotated: two sets are visible here. C: Altered ejecta clast in polymict breccia sample Y2 N6. Note contorted internal fabric and crosscutting gypsum veins. Scale shows centimetre divisions.

textured phyllosilicates. Quartz grains in two of these xenoliths exhibit multiple sets of planar elements that are indicative of shock metamorphism. Quartz crystals (up to 1.25 mm long) with up to eight sets of planar elements are also present in grain residues of three breccia splits (Fig. 5B). Debye-Scherrer XRD studies of single grains confirm the visual identification of shock deformation (Hörz and Quaide, 1973) and indicate that the quartz grains have been subjected to shock pressures ranging from ~10 to 20 GPa.

Sample Y6 N17 came from between 1295.5 and 1299 m in the Y-6 well (Fig. 4) and is compositionally similar to andesites (Table 1). It consists predominantly of a microcrystalline groundmass of plagioclase feldspars ($An_{30}Ab_{64}Or_6$ to $An_{49}Ab_{48}Or_3$), alkali feldspars ($Ab_{99}Or_0An_1$ to $Ab_{17}Or_{82}An_1$), and augite ($Wo_{45}En_{44}Fs_{11}$ to $Wo_{49}En_{17}Fs_{34}$). Minor amounts of magnetite, ulvospinel, and apatite occur interstitially. Large quartz grains or aggregates of quartz grains are scattered throughout the rock, each surrounded by coronas of medium-grained augite and feldspar that apparently nucleated on the preexisting quartz. Similar coronas are common in impact-melt rocks (e.g., Grieve, 1975), although they have also been observed around xenoliths and quartz xenocrysts in volcanic andesites and basalts (Sato, 1975). This rock lacks plagioclase phenocrysts, but does contain pods of microcrystalline feldspar. Small pockets of secondary anhydrite and calcite and quartz veins pervade the sample, indicating that the unit has been altered.

Sample Y2 N6 is a series of core fragments taken from 301 to 303 m in well Y-2 (Fig. 2). The sample is from a 90-m-thick bentonitic breccia, which is the uppermost Cretaceous unit in the well (A. E. Weidie, Jr. et al., unpublished cross section). The rock is a poorly sorted polymict breccia with angular to rounded fragments of calcareous and dolomitic limestones (sometimes fossiliferous), anhydrite, and marl; there is also one 5-cm-diameter, crudely laminated, disc-shaped clast of very poorly ordered smectite (Fig. 5C). Grain residues from two different samples of the breccia contain quartz grains with rare grains (up to 1.1 mm long) containing single and multiple planar lamellae typical of shock deformation. The large smectitic clast contains ~2% quartz and feldspar grains that also have single and multiple planar lamellae typical of shock deformation. Debye-Scherrer XRD studies on individual quartz and feldspar grains confirm the visual identification of shock deformation.

MORPHOLOGY

Because the rocks that cause the geophysical anomalies are deeply buried, the shape of the presumed circular structure is not well known. The K/T boundary within the structure is depressed ~600 to 1100 m relative to its ~500 m depth in the Ticul-1 (T-1) well (Lopez Ramos, 1975), located 5 km outside the suggested margin of the structure. A multichannel seismic reflection line ~45 km north of Progreso (Fig. 2) shows that a rough acoustic reflector, which probably corresponds to the K/T boundary, occurs at a depth of ~1500 m (Petróleos Méxicanos, unpublished data). These indicators of a depressed K/T boundary in the area of the circular anomalies, together with the presence of relatively deep water facies, suggest that a basin existed there in early Tertiary time. No obvious topographic or bathymetric expression of the circular structure exists now, although the structure may influence the near-surface groundwater regime (Pope et al., 1991).

ORIGIN

We believe that the geophysical, stratigraphic, and petrologic evidence described here strongly indicates the presence of a buried impact crater. The circular negative Bouguer-gravity anomaly, with a central high and two concentric lows, is consistent with an ~180-km-diameter peak-ring crater. The andesitic glasses and microcrystalline rocks interbedded with polymict breccias are probably a sequence of interbedded impact-melt rocks and impact breccias. Assuming a specific gravity contrast of 0.3 g/cm^3 (based on values determined for breccia sample Y6 N14 vs. the overlying sediments), an ~2 km breccia thickness would be required to produce the observed ~25 mgal negative gravity-field anomaly. Therefore, the 200–450-m-thick breccias overlying the andesitic rocks may produce the reversals in the gravity profiles by forming two peak rings, but most of the anomaly must be the result of some other mass deficiency, such as fractured basement beneath the crater. The breccias and the andesitic rocks may be the cause of the magnetic-field anomalies. Samples Y6 N14 and N17 have magnetic susceptibilities of 2.5×10^{-4} and 1×10^{-3} (cgs units), respectively, which is in contrast to the 10^{-5} to $<10^{-6}$ (cgs units) susceptibilities of the overlying sediments. Therefore, the andesitic rocks may produce, at least in part, the central high-amplitude anomalies, whereas the intracrater breccias and proximal ejecta may produce the small-amplitude anomalies that extend ~15 km past the margin of the gravity anomaly (and suggested crater rim). The depression of the K/T boundary by ~600 m indicates the presence of a basin with a depth consistent with the strength-limited depth of ~500 m expected for terrestrial impact craters (Melosh, 1989).

The Y6 N14 and Y2 N6 polymict breccias contain shocked quartz, indicating production by impact. The presence of both shocked and unshocked material in the Y6 N14 breccia and the absence of a glassy matrix (although a glass matrix could have been altered) suggests that the unit is a sedimentary breccia, which is consistent with a marine impact. The underlying Y6 N17 rock does not contain unambiguous evidence of shock-induced melting, but the presence of quartz and quartz-aggregate xenoliths, and the absence of plagioclase phenocrysts and orthopyroxene, are unusual for volcanic andesites. Microcrystalline melt rocks, apparently resulting from impact-melt bodies of sufficient size to recrystallize, are known at much smaller impact craters, such as the 28-km-diameter Mistastin Lake crater (Grieve, 1975). The required volumes of melt could easily be produced at a crater of this size; using a melt-volume scaling relation (Melosh, 1989) and a transient crater diameter of 110 km, we calculate a lower limit to the ratio of melt volume to the displaced-mass volume of 0.3. The 6 to 8 m of anhydrite intersected at the base of 380 m of andesitic rocks in well Y-6, located ~50 km from the crater center, may indicate that this is the outer and thinner part of the melt sheet.

We suggest that the breccias recorded at the K/T boundary exterior to the crater, such as the 90-m-thick breccia in well Y-2, represent the proximal ejecta blanket, because the Y2 N6 breccia contains evidence of shock metamorphism. The large smectitic clast is probably altered impact-melt ejecta, which may be analogous to Muong Nong tektites or to the Ries crater suevite bombs. The ejecta was probably mixed with locally derived sediment when it was deposited and/or was disturbed by impact waves. The back surge filling the crater may also have extensively modified parts of the ejecta blanket.

AGE

Although the available stratigraphic information provides some bounds, the age of the crater is not precisely known. Former work suggested a Late Cretaceous age for the 60 to 170 m of limestone and marl overlying the presumed impact breccias and melt rocks (Lopez Ramos, 1975). However, G. Keller and W. Sliter independently determined a late Paleocene (P3) age (based on foraminifera) for sample Y6 N12 (Fig. 4) from the limestone-marl unit (from 1000 to 1003 m depth), although the preservation is not good. Therefore, the earlier age assignment is probably invalid, and the top of the breccias could be of K/T boundary age. In addition, the 90-m-thick boundary breccia in well Y-2 probably corresponds to the crater's proximal ejecta blanket, thus indicating that the crater formed at the K/T boundary.

RELEVANCE TO THE K/T BOUNDARY

The size and location of the Chicxulub structure come close to satisfying the characteristics necessary for the K/T crater (Hildebrand and Boynton, 1990b). Because its calculated maximum excavation depth is ~15 km (Melosh, 1989) and the crust under the Yucatán platform is at least 30 km thick (Ewing et al., 1960), the crater could have excavated only continental crust. It is an attractive candidate for supplying the shocked quartz and alkali-feldspar grains found in the boundary layers (Izett, 1990), and it is well located to produce the observed size distribution and fluence of shocked grains, which are largest at Caribbean K/T sites (Hildebrand and Boynton, 1990a). The proportion of the shocked grains in the mineral residue from the Y6 N14 breccia and the Y2 N6 ejecta clast are 27% and 31%, respectively, within the range of 12% to 47% reported for 12 K/T sites (Izett, 1990).

The Chicxulub crater is also an attractive source for the K/T boundary tektites (Izett et al., 1990; Sigurdsson et al., 1991), particularly because the Haitian K/T tektites are deficient in silica relative to most tektites (Koeberl, 1986), and the Chicxulub crater has melt rocks of the necessary intermediate composition (Table 1). The composition of the Chicxulub andesitic rock is within the range observed for the K/T tektites, except for its lower Al_2O_3 and TiO_2 content. In addition, the carbonate rocks of the Yucatán platform are a good candidate source for the high-Ca tektites reported from the Haitian K/T sites (Sigurdsson et al., 1991).

However, the Chicxulub crater may not be the sole source of the boundary layers, because isotopic data (Shaw and Wasserburg, 1982) suggest that a mantle component occurs in the boundary layers, and the presence of unaltered pyroxene spherules (Smit, 1990) establishes that there is at least a small ultramafic component. Another potential difficulty is that the Chicxulub andesitic rock Y6 N17 yields an ϵ_{Nd} (65 Ma) of −5.0, which is lower than values of −2.9 (65 Ma) found in altered boundary clays (Hildebrand and Boynton, 1988) or −2.8 (66 Ma) found in tektite glass (Premo and Izett, 1991). If the Chicxulub crater were the source of the boundary ejecta, some Nd isotopic heterogeneity would be required in the andesitic melt rocks. However, the ϵ_{Sr} (65 Ma) of the andesitic rock (+55) is similar to that of the Haitian tektites (+62).

The Chicxulub crater is well located to produce the known K/T boundary ejecta. This crater is approximately equidistant between the two thickest known deposits, the 0.5–1.2-m-thick K/T ejecta found on Haiti (Hildebrand and Boynton, 1990b), which was to the southeast at K/T time, and the 0–1.0-m-thick ejecta layer found in northeastern Mexico by J. Smit, A. Montanari, N. Swinburne, and W. Alvarez (W. Alvarez, personal commun.). The Chicxulub crater might not have produced the observed suite of impact-wave deposits (Fig. 1), because it formed on a shallow-water platform a minimum of ~200 km from the deep sea, and the size of impact-induced waves is limited by the water depth at the impact site. Nevertheless, because the Chicxulub impact would be seismically equivalent to a magnitude 10 to 11 earthquake (McKinnon, 1982), it may have triggered the formation of the deep-water slump and turbidity-current deposits (which may be overlain by crater ejecta) observed at the K/T boundary at Deep Sea Drilling Project (DSDP) Sites 94, 95, 536, and 540, adjacent to the Campeche bank (Fig. 1; Buffler et al., 1984). The coarse boundary deposits in the trough present at K/T time between Cuba and the Bahamas may be seismically triggered slumps, as suggested by Pszczolkowski (1986). However, it might have been difficult for this impact to produce the distant impact-wave deposits, such as at Brazos River, Texas, or DSDP Sites 603B, 151, and 153, if the ocean on the Yucatán platform was too shallow at K/T time; therefore, a nearby, deep-water impact may have occurred at the same time.

The Chicxulub impact, having presumably produced the largest impact crater on Earth, must have caused a mass extinction, assuming that any impact can do so. In addition to prompt lethal effects, it should have produced a dramatic greenhouse warming by the shock production of CO_2 from the >3-km-thick carbonate target rocks, as suggested by O'Keefe and Ahrens (1989). Crater scaling relations (Melosh, 1989) and the size of the Chicxulub crater suggest that an order of magnitude increase in CO_2 above the current atmospheric inventory would have occurred. A temperature increase of ~10 °C for 10^4 to 10^5 years could have resulted (O'Keefe and Ahrens, 1989), causing an extended period of extinctions. The period of warmer climate could also allow for increased continental erosion to produce the K/T boundary $^{87}Sr/^{86}Sr$ spike (Hess et al., 1986).

CONCLUSIONS

The Chicxulub crater is the largest probable impact crater on Earth. Its position and target-rock composition satisfy many of the characteristics required for the K/T crater, and it may have a K/T boundary age. This impact may have caused the K/T extinctions.

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