THE CRETACEOUS/TERTIARY BOUNDARY IMPACT (OR THE DINOSAURS DIDN'T HAVE A CHANCE)*

BY ALAN R. HILDEBRAND
Geological Survey of Canada

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"How bright and beautiful a comet is as it flies past our planet – provided it does fly *past* it." – Isaac Asimov

ABSTRACT

Since Newton showed in 1687 that comets are bodies which orbit the Sun, scientists have been suggesting that comets occasionally collide with the Earth. In 1750 de Maupertuis suggested that such cometary impacts might cause the extinction of species. In 1980 Alvarez *et al.* reported the occurrence of a globally distributed, thin clay layer rich in iridium at the mass extinction level marking the 65-million-year-old Cretaceous/Tertiary (K/T) boundary with the suggestion that the layer and mass extinction were due to a large-body impact. The K/T boundary clay is now known to consist of two layers, a globally distributed, uniform ~3-mm-thick layer which was probably dispersed by the impact fireball and a layer found only near the source crater composed of ballistically distributed ejecta. Chondritic siderophile trace-element anomalies, shocked minerals and tektites have been subsequently found in the K/T boundary layers strengthening the case for a large K/T impact. In 1990 Hildebrand *et al.* showed that the source crater for the K/T impact ejecta is probably the 180-km-diameter Chicxulub crater which lies on the Yucatán Peninsula, Mexico. Knowing the size and location of the crater allows well constrained modelling of the lethal effects of the impact. The Chicxulub impact produced a massive pulse of shock-devolatized CO_2 and SO_2 because the target rocks included a thick sequence of carbonates and sulphates and was therefore particularly lethal for an impact of its size. The addition of these gases to the atmosphere led to a global sulphurous acid rain and a long-term CO_2-greenhouse warming of ~10° Celsius. The Chicxulub impact was orders of magnitude more deadly to the environment than any known terrestrial process such as volcanism. Extinction-causing impacts of this size reoccur approximately once every 100 million years thereby altering the long-term evolution of life on Earth.

RÉSUMÉ

Depuis que Newton a démontré en 1687 que les comètes étaient des corps en orbite autour du Soleil, plusieurs scientifiques ont suggéré que les comètes pouvaient parfois entrer en collision avec la Terre. En 1750, de Maupertuis suggéra que de telles collisions pourraient causer l'extinction d'espèces végétales et animales et en 1980, Alvarez *et al.* annoncèrent la découverte d'une mince couche d'argile riche en iridium distribuée globalement juste à la frontière Crétacée-Tertiaire (K/T). Cette époque, qui remonte à 65 million d'années, marque l'extinction de masse de plusieurs espèces.

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Cette découverte suggère donc un lien entre l'extinction de ces espèces et l'impact d'un corps de grande taille. L'argile à la frontière K/T se retrouve dans deux couches: la première couche, d'une épaisseur de 3 mm, recouvre la surface du globe et a probablement été projetée aux quatres coins de la planète par la force d'un impact important tandis que la deuxième couche, composée d'un éjecta ayant une distribution balistique, se trouve seulement dans les environs du cratère marquant le site de l'impact. Des anomalies dans l'abondance des éléments sidérophiles chondritiques, des minéraux ayant été soumis à des ondes de choc et des tektites ont été ensuite trouvés dans les couches à la frontière K/T renforçant ainsi la thèse de l'impact météoritique à cette époque. En 1990, Hildebrand *et al.* ont montré que le cratère de cet impact est probablement le cratère de Chicxulub d'un diamètre de 180 km sur la péninsule du Yucatán au Mexique. La taille et l'emplacement du cratère permettent de calculer avec précision les effets néfastes engendrés par cet impact. L'impact de Chicxulub a produit une élévation massive du taux de CO_2 et de SO_2 parce que les couches rocheuses sur le site de l'impact renfermaient de grandes quantités de carbonates et de sulfates qui se sont volatilisées sous la violence de l'impact. L'accroissement de ces gaz dans l'atmosphère a causé des pluies d'acide sulfurique globales et l'effet de serre résultant de la présence accrue de CO_2 a fait grimper la température globale d'environ 10°C pour une période prolongée. Les effets néfastes sur l'environnement causés par les processus terrestres connus tels que le volcanisme sont bien loin de l'ampleur de la dévastation apportée par l'impact de Chicxulub. De tels impacts semblent se produire tous les 100 million d'années altérant ainsi l'évolution à long terme de la vie sur Terre.

LS

1. Introduction. It is a pleasure and honour for me to be here to present results of research into the Cretaceous/Tertiary (K/T) boundary problem. This area of research has been the most hotly debated topic in the earth sciences since 1980, when Luis Alvarez, Walter Alvarez, Frank Asaro and Helen Michel published evidence that an impact of a large asteroid or comet with the Earth caused the mass extinction of terrestrial life observed at the K/T boundary (Alvarez *et al.* 1980) probably including the demise of the dinosaurs. I prefer to speak of the impact as ending the Cretaceous Period; the subsequent Tertiary world existed only as a consequence of the impact. The Cretaceous world would have continued and its biota would have evolved in unknown directions if the impact had not changed all of the rules of survival in an instant of geological time. The Tertiary biota did not evolve by any Darwinian survival of the fittest in competition for limited resources but through the caprice of what could survive the extreme environmental stresses imposed by the impact. We have now found the crater that was produced by the impact, establishing its occurrence beyond reasonable doubt, and can model the magnitude of the accompanying environmental disaster. Nevertheless, many in the earth science community remain uncomfortable with the impact/mass-extinction paradigm and some challenge the existence of a mass extinction at the K/T boundary or large body impacts. I believe that the formation of the Chicxulub crater buried on the Yucatán Peninsula of Mexico was responsible for causing a mass extinction of terrestrial life. Given that remarkable hypotheses require extraordinary proof, scepticism concerning the postulated large impact was justified, but evidence bearing on the problem continues to be presented, and the case for an impact is now established nearly as well as is conceivable given the lapse in time since the event. This is the story of how the crater came to be found.

2. *Historical Development of Concept.* Alvarez *et al.* (1979a, 1979b, 1980) first described geochemical and stratigraphic analyses of the K/T boundary clays indicating that an asteroid or comet impacted the Earth causing the terminal Cretaceous mass extinction. Although Alvarez *et al.* presented the first evidence supporting this theory, the concept that the impact of an extraterrestrial object might produce a mass extinction on the Earth had been repeatedly proposed for more than two centuries. Soon after Isaac Newton (Newton 1687) established that comets were distant objects which orbited the Sun (often times in Earth-crossing orbits), many scientists speculated that comets might occasionally collide with the planets, including the Earth. Pierre Louis Moreau de Maupertuis, however, was possibly the first to suggest that such impacts would cause extinctions of terrestrial biota. He suggested, in 1750, that cometary impacts with the Earth would produce heat and change the composition of the oceans and atmosphere, thus driving species extinct (de Maupertuis 1752). This idea has been often resuggested and in recent decades it has been repeatedly proposed in general or specific forms, for example by DeLaubenfels (1956), Öpik (1958), McLaren (1970) and Urey (1973). Conversely, the concept was used by Shaler in 1903 to argue that the absence of the total destruction of organic life or any record of mass extinction in the geologic record indicated that no impacts of asteroids or comets as large as 10 miles in diameter had occurred (Shaler 1903). (We now know, however, that five major mass extinctions have occurred in the Phanerozoic Era that represents the last 570 million years of Earth history (*e.g.*, Sepkoski 1982).)

The hypothesis that catastrophic impacts cause mass extinctions has been unpopular with many geologists, who have successfully employed the theory of "Uniformitarianism" to model most geologic phenomena (*e.g.*, Marvin 1990). No one has observed a large impact causing a mass extinction, so this process is inconsistent with the uniformitarian principle that the geological record was constructed by processes observed to operate today. The reality of large impact events, however, is evidenced in the cratering record of the Earth and the other terrestrial planets (*e.g.*, Carr 1984). Furthermore, the now-destroyed asteroidal and cometary projectiles which produced these craters are represented by the population of asteroids and comets that are currently observed in space. The largest impact events are statistically rare (1 per $\sim 10^8$ years; *e.g.* Grieve 1982) and would not be expected to operate on the geologically short timescale of modern science ($\sim 10^2$ years) or even human evolution ($\sim 10^6$ years). Regarding a separate but even more fundamental question, some geologists still regard the existence of ~140 known impact craters on the Earth as unproven (*e.g.*, Parkers and Toots 1989) despite compelling evidence to the contrary (*e.g.*, Grieve 1987).

In spite of the evidence supportive of a large impact at the K/T boundary, many investigators have felt that a volcanogenic origin for the boundary layers is more consistent with the available evidence (*e.g.*, Officer and Drake 1983, 1985, McLean 1985, Carter *et al.* 1986, 1990, Courtillot *et al.* 1986, 1990, Hallam 1987, Officer *et al.* 1987, Rice 1987, Crocket *et al.* 1988). This alternative hypothesis is reinforced by the existence of the Deccan flood basalts, one of the largest outpourings of basaltic lava in the latter half of the Phanerozoic (Rampino and Stothers 1988), which were erupted across the K/T boundary interval. This hypothesis, however, is inconsistent with the available data as discussed below.

3. Boundary Stratigraphy. The K/T boundary layers have a global distribution and are known from hundreds of localities making this the best known global time line in the entire geologic record with the exception of the present. Therefore, I have suggested that these boundary layers should be given formal stratigraphic status as the Chicxulub Formation defined as "the unit of rock deposited by the K/T boundary (Chicxulub) impact including material ejected from the crater, fragments of the projectile if they exist, and secondary deposits produced by the effects of the impact such as seismicity and impact waves." (Hildebrand 1992). The acceptance of this proposal is uncertain because the layers in their global extent and extreme variability in thickness represent a different type of deposit than those classified by traditional stratigraphic nomenclature. The Chicxulub formation represents a formation defined by a genetic process in addition to lithologic characteristics. As discussed by Hildebrand and Boynton (1990a), who built on the work of many other K/T studies (*e.g.*, Pillmore *et al.* 1984, Smit and Romein 1985, Preisinger *et al.* 1986, Pillmore and Flores 1987, Bohor *et al.* 1987, Hildebrand and Boynton 1988a, b), at least two layers of impact ejecta are present at the K/T boundary as shown in figure 1. Both layers are generally pervasively altered at all distal K/T localities in both marine and nonmarine depositional environments.

The upper layer, termed the fireball layer (Hildebrand and Boynton 1990a), is 2–4 mm thick (averaging 3 mm) and represents approximately 1500 cubic kilometres of debris deposited globally with no apparent variation in thickness. Even at K/T sites close to the source crater such as at Beloc, Haiti (Hildebrand and Boynton 1990a), the fireball layer apparently has the same thickness as at the most distal sites. Where not reworked this layer has sharp upper and lower contacts (figure 1). In marine sections this layer is usually a poorly ordered smectitic clay (*e.g.*, Kastner *et al.* 1984) that typically weathers a rusty orange-red colour, although it is an unspectacular grey when fresh. It may have a spotted appearance from contained submillimetre spherules. In nonmarine sections it is

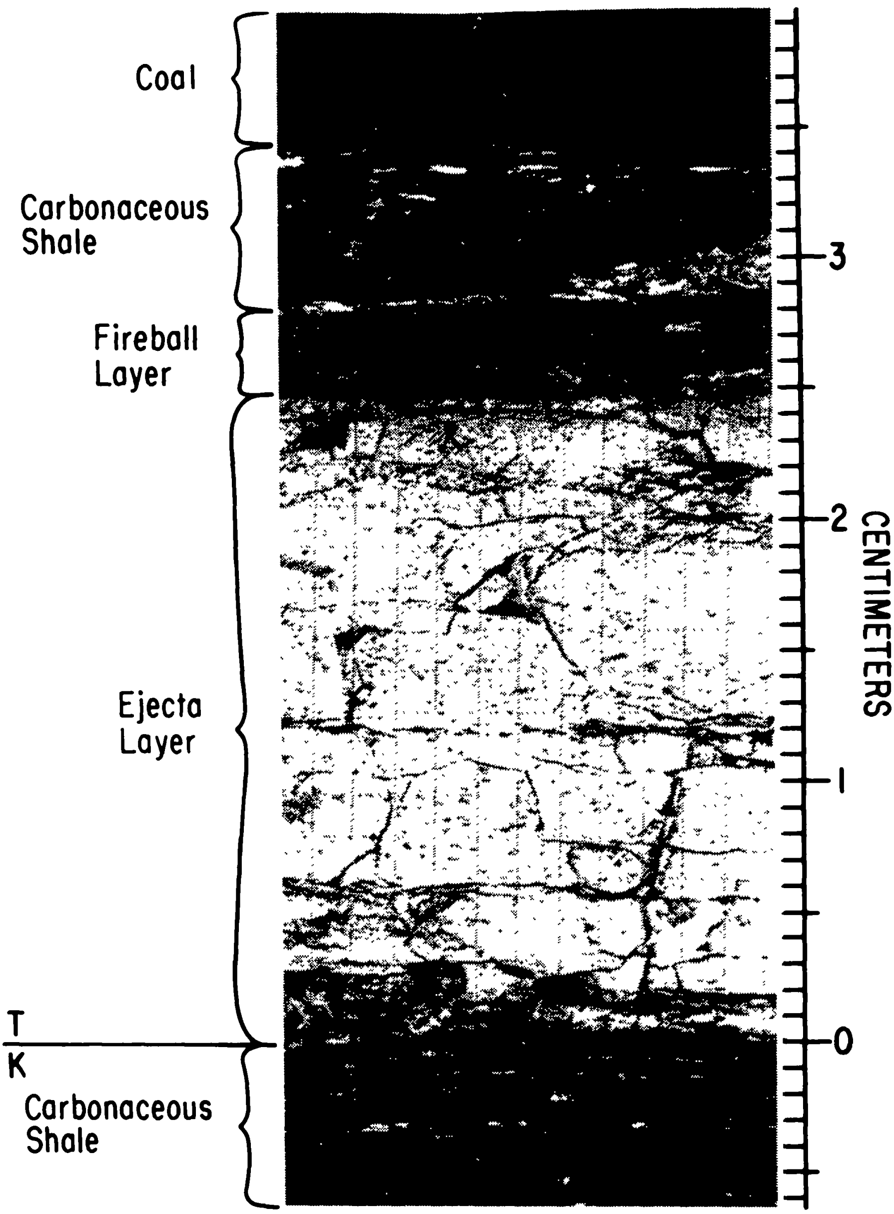

FIG. 1—This sawn slab shows the K/T boundary-layer couplet from the Starkville South locality in the Raton Basin, Colorado (*e.g.*, Pillmore and Flores 1987). The uppermost Cretaceous unit is a carbonaceous shale. The grey kaolinitized 25-mm-thick ejecta layer, here slightly tectonically thickened, is overlain by the brown, massive, 3-mm-thick fireball layer. The overlying brown, fissile, jarositic, carbonaceous shale probably represents locally reworked boundary clay material which has sometimes been included with and confused with the fireball layer (*e.g.*, Izett 1990). Coal of Tertiary age overlies the boundary sequence. This boundary layer nomenclature follows that employed by Hildebrand and Boynton (1990a). The layers have been variously disturbed by geochemical mobilization, erosion and redeposition, syn-sedimentary deformation, bioturbation, tectonism, and/or weathering at all known localities, necessitating care in separating primary and secondary characteristics. The layers preserved in nonmarine sequences such as this one in the Raton Basin usually have suffered less disturbance to their presumed original stratigraphy than those preserved in marine sequences.

typically a massive brown unit composed dominantly of smectitic clay but it is grey and kaolinitic at some localities.

The fireball layer contains anomalously large amounts of the highly siderophile trace elements (Ru, Rh, Pd, Re, Os, Ir, Pt, and Au) in chondritic proportions (*e.g.*, Kyte *et al.* 1985). Enrichments of the platinum group elements are often referred to when discussing the K/T problem but Re and Au are not part of the platinum group. The chalcophile trace elements (*e.g.* As, Sb, Se, Zn, and Hg) are also found in anomalous amounts in this layer in both marine (*e.g.*, Gilmore and Anders 1989) and nonmarine (*e.g.*, Hildebrand and Wolbach 1989, Schmitz 1992) sections. This layer contains shocked mineral grains of quartz, quartzose sediments and metasediments, feldspars, granitoid rocks, chromites and zircons (*e.g.*, Bohor *et al.* 1984, Bohor *et al.* 1989, Izett 1990, Krogh *et al.* 1992). The shocked grains occur in amounts ranging from ~1% to trace abundances depending upon proximity to the source crater as discussed below. Spinels of unusual composition are found in this layer frequently occurring in skeletal and dendritic patterns within submillimetre spherules (*e.g.*, Montanari *et al.* 1983, Kyte and Smit 1986, Bohor *et al.* 1986). Now-pseudomorphed microtektites and tektites also occur as other types of "spherules" (*e.g.*, Smit and Klaver 1981, Bohor and Betterton 1990, Montanari 1991). This layer also has anomalously large concentrations of soot from burning wood (*e.g.*, Wolbach *et al.* 1985, Wolbach *et al.* 1988, Wolbach *et al.* 1990).

The secondary minerals that comprise the bulk of the fireball layer have slightly unusual Sm-Nd isotope systematics showing $^{143}Nd/^{144}Nd$ ratios intermediate between those characteristic of continental and oceanic terranes (*e.g.*, Shaw and Wasserburg 1982, DePaolo *et al.* 1983, Hildebrand and Boynton 1988b). The incompatible trace elements, such as the rare-earth elements, are usually depleted relative to their concentrations in typical continental sediments (*e.g.*, Smit and ten Kate 1982, Hildebrand and Boynton 1987). In contrast, compatible trace elements are usually enriched at the nonmarine sites (*e.g.*, Gilmore *et al.* 1984). These trace-element characteristics are a consequence of the alteration of the original fine-grained fallout debris and may not be used to infer the provenance of the layer's material. The original bulk composition of the fireball layer is assumed to be similar to that of the tektite glass of the underlying ejecta layer (described below) with an admixture of ~10% of the dispersed projectile based on siderophile trace-element abundances (*e.g.*, Kyte *et al.* 1985). Hildebrand and Boynton (1988a, b, 1990a) called the upper layer the fireball layer, implying its dispersal by the impact fireball formed by vaporization of the projectile and target material (*e.g.*, Jones and Kodis 1982, Vickery and Melosh 1990).

An ~2-cm-thick layer, termed the ejecta layer (Hildebrand and Boynton 1990a), has been known to underlie the fireball layer at most localities in western Canada and the U.S.A. (figure 1) since 1984 (Pillmore *et al.* 1984). Beginning in 1989, much thicker stratigraphic equivalents, up to ~2.5 m thick, have been discovered in the region between the Americas (*e.g.*, Hildebrand and Boynton 1990a, Smit *et al.* 1992, Alvarez *et al.* 1992). The lower layer has been described only from North American and Caribbean environs (figure 2). It has not been found as a discrete layer in Europe, Asia, the southern Atlantic or the western Pacific regions. Izett (1987, 1990) has argued that this underlying layer was not impact-derived, but represented a product of pedogenesis or was analogous to a coal underclay. The occurrence of this layer in marine sections, however, and the recent discovery of tektite glass in the layer have established its impact origin. Where not reworked this layer has sharp upper and lower contacts (figure 1). This layer was completely altered to a featureless kaolinitic claystone at the localities where it was first discovered, but was later found to contain abundant ~1 mm spherules (Klaver *et al.* 1987, Bohor *et al.* 1987a) which were eventually interpreted as probably pseudomorphed microtektites and tektites (*e.g.*, Klaver *et al.* 1987, Bohor and Betterton 1988, Hildebrand and Boynton 1990a, Smit 1990). At the Rick's Place locality near Brownie Butte, Montana, the bottom of the layer is formed from the tightly packed shapes of the individual ~1 mm-sized tektites which deformed the soft Upper Cretaceous mud into which they sank. Later the independent discovery of unaltered tektite glass in the ~50-cm-thick Haitian ejecta layer by several groups (*e.g.*, Izett *et al.* 1990, Sigurdsson *et al.* 1991a) further supported the impact origin of the spherules. The ejecta layer frequently contains shocked minerals but this component may represent mixing and sorting of the shocked minerals of the fireball layer such that they contaminate the ejecta layer. The ejecta layer, including the unaltered tektite glass, shows the same intermediate Nd isotopic signature as the fireball layer (Hildebrand and Boynton 1988b, Premo and Izett 1991). The altered ejecta layer also typically shows the low abundances of incompatible lithophile elements and high amounts of compatible elements as found in the fireball layer (Gilmore *et al.* 1984, Hildebrand and Boynton 1987, Hildebrand and Boynton 1990a), but the incompatible elements are also enriched at some sites (*e.g.*, Bohor and Meier 1990). These trace-element patterns are now also ascribed wholly to the alteration process. Hildebrand and Boynton (1990a) called this layer the ejecta layer implying it represented a geographically restricted facies of less-energetic, ballistically distributed impact ejecta as first tentatively suggested by Smit and Romein (1985).

4. Evidence of a K/T Impact. In the decade since Alvarez *et al.* (1979a, 1979b, 1980) proposed that an asteroid or comet impacted the Earth causing the K/T mass extinction, a wide array of physical, chemical and isotopic evidence has been accumulated supporting an impact termination of the Cretaceous Period. The six most persuasive lines of evidence are: (1) the boundary stratigra-

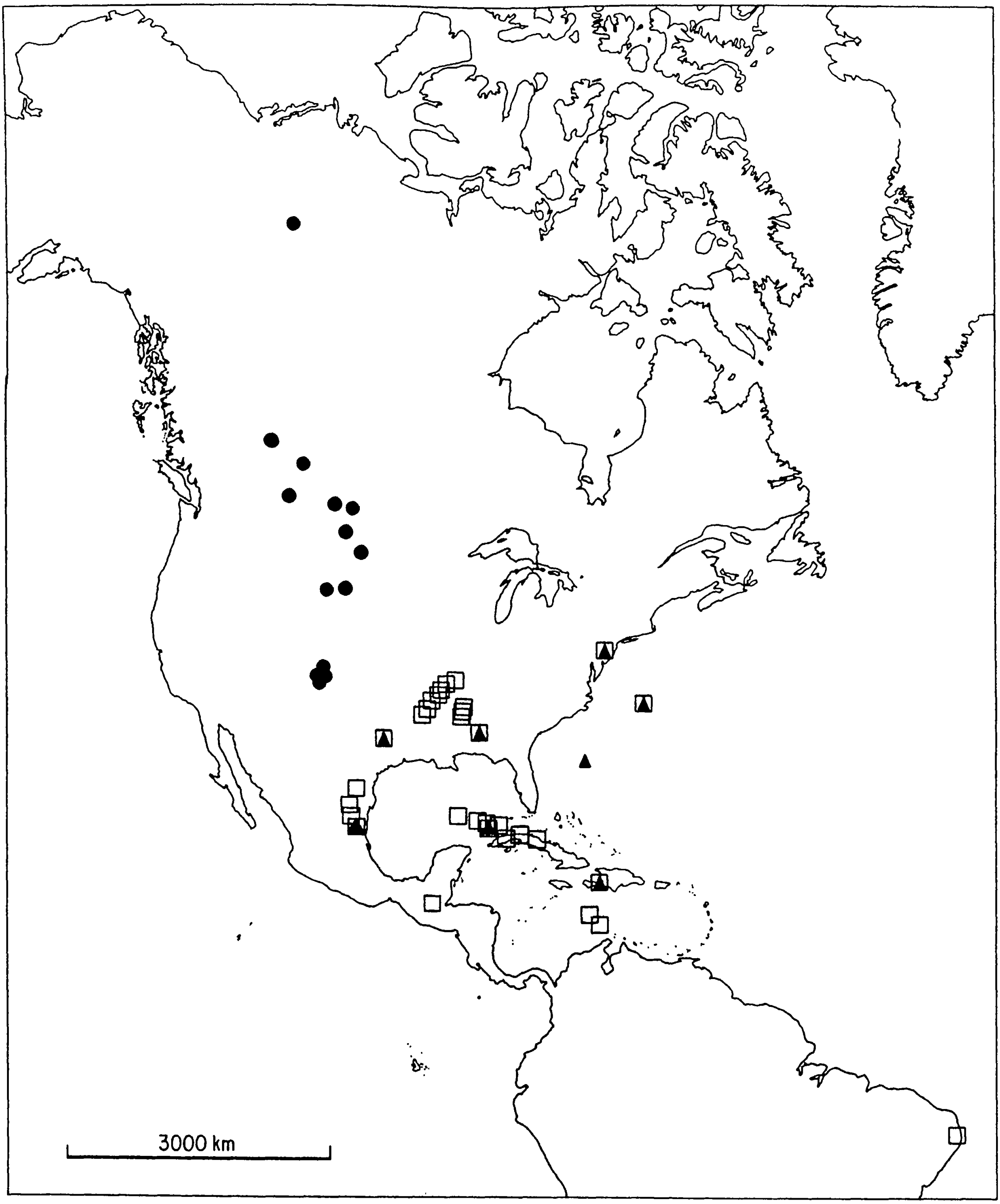

FIG. 2—North American and Caribbean K/T ejecta layer localities. Solid circles represent non-marine boundary localities with geochemical anomalies; solid triangles represent marine boundary localities with geochemical anomalies and/or boundary layers; open squares represent marine boundary localities with possible impact-wave deposits. The ejecta layer is present at all the localities represented by the solid circles and squares. A discrete ejecta layer is not recognized at any other sites on the globe. The three ejecta sites in the Caribbean and Mexico are one to two orders of magnitude thicker than those farther north suggesting that the impact location is nearby.

phy occurs globally with a uniformly-distributed fireball layer, (2) the highly siderophile trace elements occur in the fireball layer in large amounts (~10% of chondritic abundances) and (3) in chondritic proportions, (4) shocked mineral grains and (5) tektites occur in the boundary layers, and (6) the Chicxulub crater, an impact crater buried in Yucatán, Mexico, is suitably located and sized to produce the boundary layers. Other lines of evidence also indicate that something caused unusual or environmentally disastrous effects at the K/T boundary, including the mass extinction of terrestrial biota, for example, the carbon and oxygen stable isotope anomalies, the spinel phases of unusual composition and the global occurrence of large amounts of soot. Alvarez (1987) discusses some of these other lines of evidence. The six main lines of evidence are discussed below in detail.

(1) The K/T boundary layers have been described from around the world and most investigators agree that the layers reflect a global event. All the complete (defined as having all the recognized microfossil and palaeomagnetic zones) and undisturbed K/T boundary sequences examined to-date contain the fireball layer. The model of a thin, ~3-mm-thick, stratum, which has been subsequently disturbed by secondary processes, can account for the stratigraphy which I observed at ~50 K/T boundary localities, and for all the published observations of others (although this model is not subscribed to by some researchers). Separating the primary depositional signal from secondary effects remains a partly intuitive and, therefore, subjective task. Because the fireball layer is the same thickness globally, its rapid dispersal and an energetic origin are indicated. This layer was deposited in a wide range of marine and nonmarine environments with average sedimentation rates ranging from 0.005 mm/yr to 0.15 mm/yr (Smit and Hertogen 1980, Theide and Rea 1981, Smit and Romein 1985, Lerbekmo and St. Louis 1986, Preisinger *et al.* 1986), but the layer is always 2–4 mm thick. Therefore, the sedimentation rate for the fireball layer must have been faster than the fastest rate recorded for the enclosing sediments. This is inconsistent with volcanic scenarios (*e.g.*, Officer *et al.* 1987) which require 10,000 years or more for the layer's emplacement as then the background sedimentation rates would control the layer's thickness. Dust-settling models for the impact suggest that the material of the fireball layer was deposited in a period of 2 to 3 months (*e.g.*, Toon *et al.* 1982), implying an average sedimentation rate of 10 to 20 mm/yr. (The dust-settling models indicate that the bulk of the layer was actually deposited more quickly.) This rapid rate is consistent with and required by the background sedimentation rates described above. No known endogenic process, such as volcanism, can deposit 1500 km^3 of material globally, uniformly, and in less than a year. This is, however, consistent with the impact scenario.

(2, 3) The fireball layer contains the highly siderophile trace elements in approximately chondritic-meteorite proportions at an abundance level of 10 to 15% that of CI chondrites (*e.g.*, Ganapathy 1980, Kyte *et al.*, 1980, Smit and Hertogen 1980, Kuslys and Krähenbühl 1983, Kyte *et al.* 1985, Lerbekmo and St. Louis 1986, Bohor *et al.* 1987a, Orth *et al.* 1987, 1990, Bekov *et al.* 1988, Tredoux *et al.* 1989, Geissbühler 1990)—1,000 to 10,000 times higher than typical crustal abundances and ~20 times higher than mantle abundances (*e.g.*, Chou *et al.* 1983). Figure 3 shows an Ir-abundance profile across the Knudsen's Farm K/T boundary sequence which was featured on the field trip this afternoon. An impact of an extraterrestrial object can produce siderophile trace-element anomalies similar to the K/T boundary anomalies as shown by Kyte and Brownlee (1985), who described meteorite fragments in an ejecta layer with an associated iridium anomaly in deep-sea sediments from the South Pacific Ocean, or by Gostin *et al.* (1989) who describe chondritic-ratio anomalies of Ir, Ru, Au, Pt and Pd associated with the ~600-Myr-old Acraman crater ejecta horizon found in southern Australia. Therefore, an impact of a large undifferentiated asteroid or comet could have produced the siderophile trace-element-rich layer. The isotopes of Ir (Alvarez *et al.* 1980), Re (F. Asaro personal communication, Rocchia *et al.* 1988), and Os (Smit and Hertogen 1980) are present in solar system proportions in the K/T fireball layer, implying that other extraterrestrial events, such as a nearby supernova explosion, may be ruled out as the source of the siderophile trace-element anomaly. Additionally, searches for the radioactive products of a supernova in the boundary layers have proved negative (*e.g.*, Gilmore *et al.* 1984).

Basaltic volcano aerosols have been suggested as a possible source for the siderophile trace elements in this layer (*e.g.*, Zoller *et al.* 1983, Officer and Drake 1985), but aerosols from the Hawaiian volcanoes contain Ir, Au and Re in ratios nonchondritic by three orders of magnitude (Zoller *et al.* 1983, Hildebrand *et al.* 1984, Olmez *et al.* 1986, Crowe *et al.* 1987, Finnegan *et al.* 1990). Because the strongly non-chondritic ratios in the aerosols apparently reflect the elemental abundances in the erupting volcanic melts, which in turn reflect these elements' differing partitioning behaviour during generation of partial melts in the mantle (Chou *et al.* 1983), aerosols of all basaltic volcanoes will probably show siderophile trace-element ratios similar to those of the Hawaiian volcanoes. This has been partly confirmed by analysis of vapour deposits from the Piton de la Fournaise volcano at the Reunion Island hotspot, where Au to Ir ratios have been found to be nonchondritic in a similar sense, although of a smaller magnitude (Toutain and Meyer 1989).

The fireball layer has a primitive $^{187}Os/^{186}Os$ ratio of approximately 1 (*e.g.*, Luck and Turekian 1983, Lichte *et al.* 1986, Krähenbühl *et al.* 1988, Geissbühler 1990), the same as that found in undifferentiated meteorites, but differing from the value of ~10 found in crustal rocks (*e.g.*, Turekian 1982). This eliminates the possibility of a crustal provenance for the anomalies (*e.g.*, Schmitz 1985) at least for this siderophile trace element. The Os found in the mantle and erupted

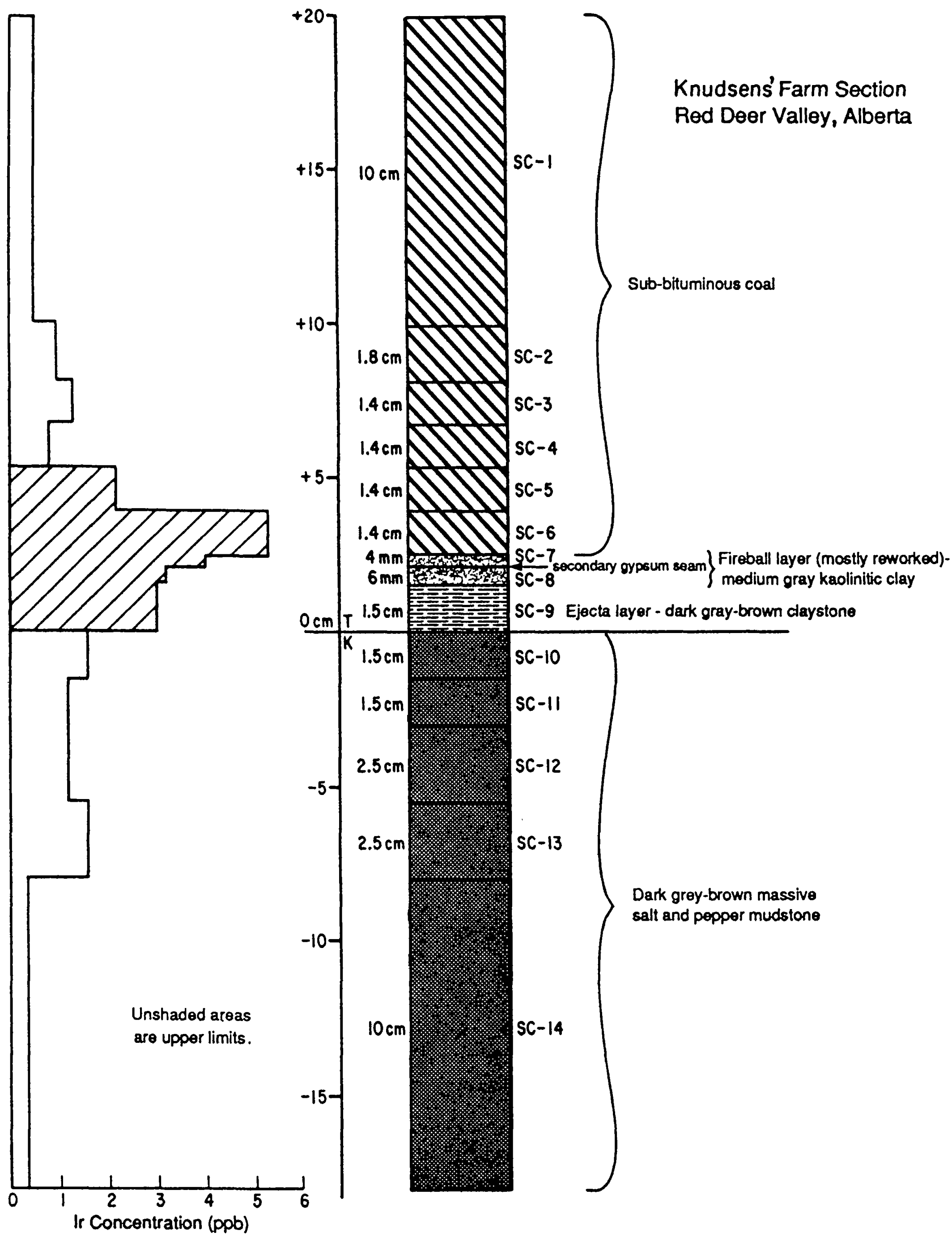

FIG. 3—An iridium abundance profile across the Knudsens' Farm K/T boundary locality. A more comprehensive study of the siderophile trace elements across this sequence by Lerbekmo and St. Louis (1986) established that the background abundance of Ir is at least as low as 50 parts in 10^{12} so that the Ir abundance anomaly is at least 100 times background levels. The Ir peak abundance occurs in the base of the coal seam reflecting partial geochemical mobilization of this element from the fireball layer to the reducing environment of the coal. Lerbekmo and St. Louis determined that Au, Pt, Os and Rh are also present in anomalous amounts and in roughly chondritic proportions in this sequence.

from mantle-sourced volcanoes, however, also has approximately the chondritic ratio (*e.g.*, Luck and Turekian 1983, Geissbühler 1990). Therefore, this evidence does not provide a means to distinguish between a mantle and extraterrestrial source.

(4) Mineralogic evidence of shock metamorphism was first found in the K/T boundary layers in 1984 in the form of quartz grains with multiple sets of planar deformation features (Bohor *et al.* 1984). The characteristics of planar deformation features (or shock lamellae) produced in quartz have been well-described from natural and artificial shock environments (*e.g.*, French and Short 1968). Since the initial discovery of the shocked quartz grains, Izett and Pillmore (1985) discovered that they were concentrated in the fireball layer and shocked minerals, including shocked feldspars, have been found in the fireball layer as a ~1% to trace component at sites from around the globe (*e.g.*, Badjukov *et al.* 1986, Bohor and Izett 1986, Preisinger *et al.* 1986, Bohor *et al.* 1987b, Izett 1990, Sharpton *et al.* 1990, Hildebrand and Boynton 1990a). In some cases, the shocked quartz is also found in the ejecta layer, although this probably usually reflects mixing of the components of the two layers. Shocked chromites (Bohor *et al.* 1989) and zircons (Krogh *et al.* 1992) have also been described from the fireball layer.

Claims have been made that the quartz and feldspar grains produced by felsic volcanism show shock effects similar to those found at impact craters and the K/T boundary layer (*e.g.*, Carter *et al.* 1986), but these have been refuted (*e.g.*, Alexopoulos *et al.* 1988, Owen and Anders 1988, Sharpton and Schuraytz 1989, Owen *et al.* 1990). However, considerable controversy was still apparent among K/T boundary researchers at the end of the decade (*e.g.*, Grieve *et al.* 1990) concerning the validity of some published reports describing the identification and distribution of shocked quartz at the K/T boundary.

Searches have been made for other mineralogic evidence of shock metamorphism, such as the occurrence of high pressure polymorphs of silica, coesite and stishovite. Bohor *et al.* (1984) and McHone *et al.* (1989) reported the detection of stishovite in K/T boundary residues, but Izett (1990) has been unable to reproduce some of the results of Bohor *et al.* or McHone *et al.* and questions the validity of these previous studies.

Another indicator of shock metamorphism has been discovered by Carlisle and Braman (1991) who found 3 to 5 micrometre-sized crystals of diamond in a residue of the fireball layer. Gilmour *et al.* (1992) confirmed this discovery by finding diamonds in the same layer at two different K/T localities. Carlisle (1992) advocated that the diamonds are a remnant of the projectile based on their C isotopic composition but Gilmour *et al.* provided more detailed C and N isotopic evidence indicating that the diamonds are probably derived from a terrestrial source. They were probably formed by the shock-induced transformation of carbonaceous phases in the rocks targeted by the impact. The latter scenario also seems preferable because the impacting projectile was probably mostly vaporized in the impact and therefore unable to provide the quantity of diamond observed in the fireball layer.

(5) Unaltered tektites and microtektites have recently been found in the K/T boundary ejecta layer. This further establishes that it is an ejecta layer as tektites are generally accepted as impact products (*e.g.*, Glass 1984, Koeberl 1986). The glass provides the best provenance information for the K/T boundary crater target rocks available to-date. Sanidine spheroids, dumbbells and discs in the fireball layer as preserved at Caravaca, Spain, had been suggested as projectile ablation spherules or, in passing, as microtektites by Smit and Klaver as early as 1981 (Smit and Klaver 1981). Ejecta-layer spheroids, composed of alteration products, had been described as early as 1987 from the ~2-cm-thick ejecta layer from a nonmarine site in Wyoming (Bohor *et al.* 1987a) and DSDP site 603B off New Jersey (Klaver *et al.* 1987). These spheroids are apparently distinct from the spinel-bearing spheroids found earlier in the fireball layer (*e.g.*, Montanari *et al.* 1983, Smit and Kyte 1984), although the two types of spheroids may be mixed together in distal sections where only a single layer is present. Klaver *et al.* interpreted the spherules as altered impact-produced glass, but Bohor *et al.* did not interpret the spheroids as pseudomorphed tektites until 1988 initially interpreting them as outgassing products.

In 1989, clay-altered spheroids (figure 4) up to 10 mm in size from a 50-cm-thick K/T boundary layer preserved near Beloc, Haiti, were described and interpreted, on the basis of the observed morphologies being identical to those of altered splashform tektites and microtektites, as pseudomorphed tektites and microtektites (Hildebrand and Boynton 1989a, 1990a). This layer had previously been interpreted as a thick volcanogenic deposit, although it was once noted that a minor component of microtektites might be present (Maurrasse 1980). Subsequently, different groups of investigators independently discovered unaltered glass cores in the pseudomorphed tektites establishing their impact origin (Izett *et al.* 1990, Sigurdsson *et al.* 1991a,). The tektite glasses have an intermediate composition, being slightly more depleted in silicon than other tektite groups, but are clearly derived from continental crust. This irrefutably established the provenance of the K/T boundary impact as continental crust consistent with the evidence of the shocked mineral assemblages found in the boundary layers. Sigurdsson *et al.* (1991a, b) discovered the widest range of tektite compositions from the Beloc locality, including high-calcium tektites, confirmed by Maurrasse and Sen (1991), establishing that carbonates had to be present at the impact site. Subsequent discoveries of other thick K/T boundary ejecta layers between the Americas have established the widespread distribution of unaltered K/T boundary tektites (*e.g.*, Smit *et al.* 1992, Alvarez *et al.* 1992) and have extended the range of melt glass compositions even further, although a carbonate-covered continental target is still indicated. The compositions and distribution of the tektites (and all other types of K/T boundary deposits and ejecta) are consistent with origination of the tektites at the Chicxulub crater which will be discussed below.

5. Locating the Source Crater. Since Alvarez *et al.* (1980) published evidence that a large impact might have occurred at the K/T boundary, the geological community has been searching for the crater. This search was frustrated by the fact that approximately half the ocean floor extant at the end of the Cretaceous has been subsequently subducted (*e.g.*, Parsons 1982), raising the possibility that the K/T crater had been destroyed. In the following years, impact sites were suggested all over the globe on the basis of large (200–300 km diameter) crudely circular geological structures or any significant geologic event with a perceived age of ~65 million years. See Alvarez *et al.* (1982) for a discussion of some early suggested locations. Some suggestions were based on perceived maxima in Ir fluences in the K/T boundary layer but the integrated amounts of Ir vary at the whim of erosion and redeposition so that the centres of local basins will often contain fluences of ~500 ng cm^{-2} versus nearby sections which contain one to two orders of magnitude less (*e.g.*, Alekseyev *et al.* 1988), indicating that this line of reasoning is invalid. The global average fluence is best estimated as 40 to 50 ng cm^{-2} of Ir (*e.g.*, Gilmore *et al.* 1984, Kyte *et al.* 1985) and no good evidence of any gradient in Ir fluence is yet available.

The apparently successful search for the crater did hinge on following clues from the boundary layers. In 1984, French suggested that the intrinsically large size (~0.1 mm) of the shocked quartz grains indicated that the impact site has to be nearby (*i.e.*, on North America consistent with the work of Bohor *et al.* (1984), who suggested that the occurrence of quartz grains indicated a continental target) on the basis of dust settling calculations (French 1984). French further suggested that, of the two known young craters on North America, Manson and Sierra Madera, the Manson crater in Iowa was the best candidate. It is now known that shocked quartz grains of this size are distributed globally (*e.g.*, Bohor *et al.* 1987b), but also that the impact is indeed near North America—so this suggestion was based on incomplete evidence but turns out to be right. In 1985, the argument of intrinsic size was repeated by Izett and Pillmore, who had discovered quartz grains up to 0.55 mm diameter in the western United States, which is a larger size than found globally. In the same year, Smit and Romein (1985) suggested that the presence of the recently-recognized, ~2-cm-thick ejecta layer underlying the fireball layer in the western United States might be a geographically-restricted ejecta deposit whose presence indicated that the crater was nearby. They also suggested that the course sediments preserved at

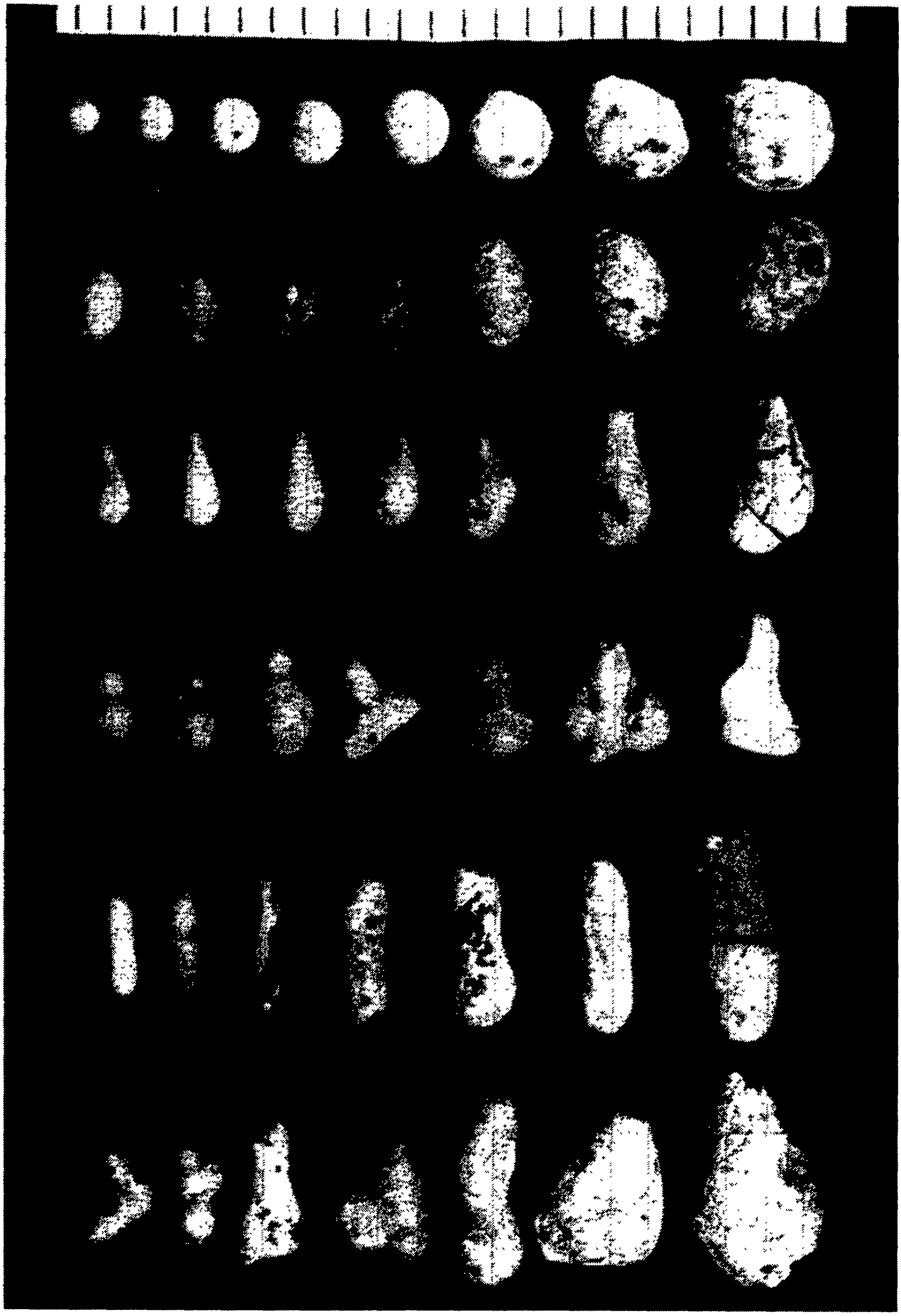

FIG. 4—Examples of Haitian K/T ejecta layer tektites now pseudomorphed by poorly ordered smectitic clay. Spheres, discs, ovoids, teardrops, ellipsoids, dumbbells and irregular shapes are shown. Examples of fused spheres and teardrops are also present. Rods are also present in the ejecta layer but are difficult to separate whole from the matrix.

the marine shelf K/T boundary locality on the Brazos River might be a tsunami-produced deposit from an implied nearby oceanic impact. Thus, by 1985 the three criteria which were to prove most useful in tracking down the location of the crater, shocked-mineral grain size, ejecta-layer thickness, and impact-wave deposits, had already been published.

In 1986, Bohor and Izett suggested that the impact site was near western North America on the basis of the relatively larger size of the shocked grains occurring in the Western Interior versus European and New Zealand sites. This criterion remains valid and the largest known shocked grains are found near the crater (*e.g.*, Hildebrand 1992, figure 5). Kyte and Smit (1986) suggested that variations in the composition of the unusual spinels preserved in the fireball layer might provide a clue to the impact location, but, because of the paucity of sites known to have spinels and the variation in spinel composition recorded at each site, this suggested location criterion was not very useful. Unknown to many K/T researchers, Pszczolkowski (1986) published a description of very thick, coarse sedimentary K/T boundary deposits in Cuba together with the possible implication that they might be indicators of a nearby impact locale.

In 1987, Orth *et al.* suggested that the ejecta layer thickened from north to south in the western United States, although local variation in the layer's thickness is as much as the perceived variation (a factor of two). Izett (1987) suggested that the relative size and fluence of shocked mineral grains indicated a nearby continental impact site. Hildebrand and Boynton (1987) suggested an impact site in the eastern Pacific near southern North America on the basis of the geographically restricted ejecta layer and the potential impact-wave deposit located at Brazos River, Texas. These indicators, based on the boundary layer components and stratigraphy, were becoming of more interest to the K/T boundary community, although impact sites were still suggested at diverse locations around the globe (*e.g.*, Hartnady 1987). In 1988, Hildebrand and Boynton (1988a, c, d) suggested an impact site near southern North America on the basis of combining all these criteria with emphasis on the potential impact-wave deposits preserved on southern North America and the Caribbean, which yielded a focus on the Colombian Basin of the Caribbean Sea. The impact-wave criterion was also used by Bourgeois *et al.* (1988) to suggest an oceanic impact site within a larger, but overlapping, region.

5.1. Proximal K/T Ejecta on Haiti. Use of the impact-wave criterion to locate the K/T impact site between North and South America proved unpopular with most of the K/T community, particularly with those researchers who felt that the impact had targeted a continent rather than an ocean basin. (Ironically, it was eventually discovered that everyone was partly right; the K/T impact targeted submerged continental rocks and thereby produced impact-wave deposits.) To

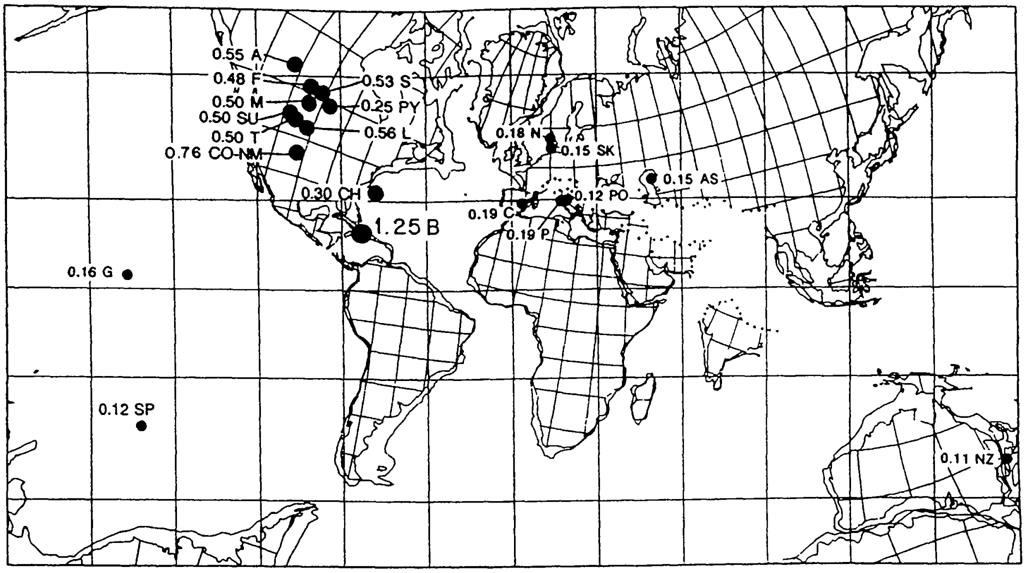

FIG. 5—Global shocked-quartz grain-size distribution plotted on a plate tectonic reconstruction for K/T time (Modified from Izett 1990). Grain size of the largest shocked quartz grain found at a K/T locality is reported in mm. Localities are positioned with dots; dot sizes schematically correspond to the size of the largest quartz grain at a locality. Note the large grains on the North American continent and the largest grain at Haiti. The deep-sea core sites represented by CH and G have not been well enough sampled to know what the largest grain size is that will be found at these sites. Locality abbreviations are: A, Knudsens' Farm, Alberta; F, Frenchman River, Saskatchewan; S, Morgan Creek, Saskatchewan; M, Brownie Butte, Montana; PY, Pyramid Butte, North Dakota; SU, Sussex, Wyoming; T, Teapot Dome, Wyoming; L, Dogie Creek, Wyoming; CO-NM, Raton Basin, Colorado and New Mexico (data from Sharpton 1989); B, Beloc, Haiti, (data from Hildebrand 1992); CH, DSDP site 603B; G, GPC-3, Giant piston core; SP, DSDP site 596 (data from Zhou *et al.* 1991); N, Nye Klov, Denmark; SK, Stevns Klint, Denmark; C, Caravaca, Spain; P, Petriccio, Italy; PO, Pontedazzo, Italy; AS, Turkmenia, USSR; NZ, Woodside Creek, New Zealand.

test this hypothesis further I searched for thick K/T ejecta at nearby localities and in 1989 discovered that an ~50-cm-thick ejecta layer occurred on Haiti by studying samples of an unusual Haitian K/T boundary deposit collected by Florentine Maurrasse (Hildebrand and Boynton 1989).

Maurrasse had discovered and described (*e.g.*, Maurrasse *et al.* 1979, Maurrasse 1980, 1982) a deep-water sequence of limestone ~150 m thick (the Beloc Formation) which spanned the K/T boundary on the hill tops of the Massif de la Selle on the southern peninsula of Haiti. He found three "volcanogenic turbidites" within the limestones, the thickest (~50 cm thick) one occurring below but near the K/T boundary. A volcanogenic origin was ascribed to the boundary turbidite based on the types of minerals found in residues of the layer and its being similar in appearance to weathered volcanic rocks of the region. Water depths during deposition exceeded ~2 km, but the formation was deposited above the CCD (carbonate compensation depth) as evidenced by the good preservation of the foraminifera (Maurrasse and Sen 1991).

The thick boundary unit found in the Beloc Formation and subsequently interpreted as the K/T ejecta layer (*e.g.*, Hildebrand and Boynton 1990a) is known to occur at the K/T boundary because of biostratigraphic constraints. Maurrasse *et al.* (1979) report that the underlying limestone unit contains the uppermost Cretaceous index foraminifera (Zone M3) *Abathomphalus mayaroensis* and that the overlying limestone contains the lowermost Paleocene index forams (Zones P0 and P1a) *Guembelitria cretacea* and *Globigerina eugubina*. Sigurdsson *et al.* (1991a) confirm these results and reported that the overlying P0 Zone is 5 cm thick in the section they studied. They also found that the boundary ejecta unit lies above the latest Cretaceous nannoplankton *Micula murus* Zone and its top 6.75 m below the Early Tertiary *Biscutum romeinii* Subzone (NP1). Thus, both the foraminifera and nannoplankton records place the coarse unit at the K/T boundary.

Figure 6 shows the K/T ejecta layer at the site which (from field studies) best preserves the original depositional history (*e.g.*, Hildebrand 1992). This exposure is part of a long outcrop where up to 50 m of the Upper Cretaceous limestones are exposed. These are weakly bedded (~10 to 30-cm-thick beds), very fine-grained, massive, light grey conchoidal to hackly fracturing limestones. The uppermost Cretaceous sediments are overlain by the ejecta layer, a greenish-brown, 46-cm-thick, single graded bed composed of mm-sized pseudomorphed tektites. The layer grades from coarse to fine and dark to light from bottom to top. The layer is separated from the underlying Cretaceous limestone by a 5- to 15-cm-thick weathered clay-rich fault gouge. Faulting subparallel to bedding is common at the margins of the boundary layers throughout the area of the Beloc Formation and presumably reflects the mechanical contrast between the clay and limestone lithologies. The top 2 cm of this 46-cm-thick clay layer contain diffuse light to medium-grey clay-rich carbonate layers which have been disturbed by fine-scale bioturbation. The graded layer is a thick ejecta layer because it is composed of tektites (now mostly pseudomorphed) and a trace of shocked minerals. The overlying thin grey clay layer is the equivalent to the fireball layer based on its containing anomalous amounts of Ir and other siderophile trace elements (*e.g.*, Alvarez *et al.* 1982, Hildebrand 1992, Jéhanno *et al.* 1992). Figure 7 shows the fireball layer overlying the ejecta layer at another nearby K/T site. The layers are overlain by light brown Tertiary limestones although another fault separates these from the graded boundary layers at the site pictured in figure 6. These limestones are somewhat more thinly bedded than the underlying Cretaceous limestones although the unit's fracturing is similar.

Many investigators have subsequently studied the Haitian boundary deposits. Most have agreed that the K/T ejecta layer is just that (*e.g.*, Izett 1991, Sigurdsson *et al.* 1991a, b, Maurrasse and Sen 1991, Koeberl and Sigurdsson 1992,

FIG. 6—Road outcrop exposing a 46-cm-thick K/T boundary ejecta layer near Beloc, Haiti. Bedded, hackly fracturing uppermost Cretaceous limestones are overlain by a graded layer composed of tektites pseudomorphed by clay. The hammer head rests on the top of the ejecta layer. Darker Tertiary limestones overlie the ejecta layer in fault contact with it and other ejecta layer blocks.

Blum and Chamberlain 1992). However, some have argued that the ejecta layer (and in some cases the fireball layer) formed as the result of volcanism (*e.g.*, Lyons and Officer 1992, Jéhanno *et al.* 1992). Most of the properties of the layers are consistent with formation by impact and are inconsistent with a volcanic origin and subsequent discoveries have removed some of the objections (*e.g.* the lack of lechatelierite) while providing new evidence in favour of the impact model (*e.g.* elemental and isotopic compositions inconsistent with a volcanogenic origin and additional thick ejecta localities scattered across 2,000 km) so that a volcanic origin does not seem to be a valid alternative based on the currently available evidence.

The Haitian ejecta layer is ~25 times as thick as the ejecta layers found in Canada and the United States (and nearby offshore areas as shown in figure 2) which were the only other examples known at the time of its discovery. This strongly indicated that the K/T impact site had to be comparatively near Haiti. This indication of proximity was reinforced by the occurrence of the largest shocked-quartz grains, largest pseudomorphed tektites, and largest fluence of shocked-mineral grains at the Haitian sites (*e.g.*, Hildebrand 1992).

From a calculation based on the observed ejecta-layer thickness and an ejecta-thickness scaling relation (McGetchin *et al.* 1973), Hildebrand and Boynton

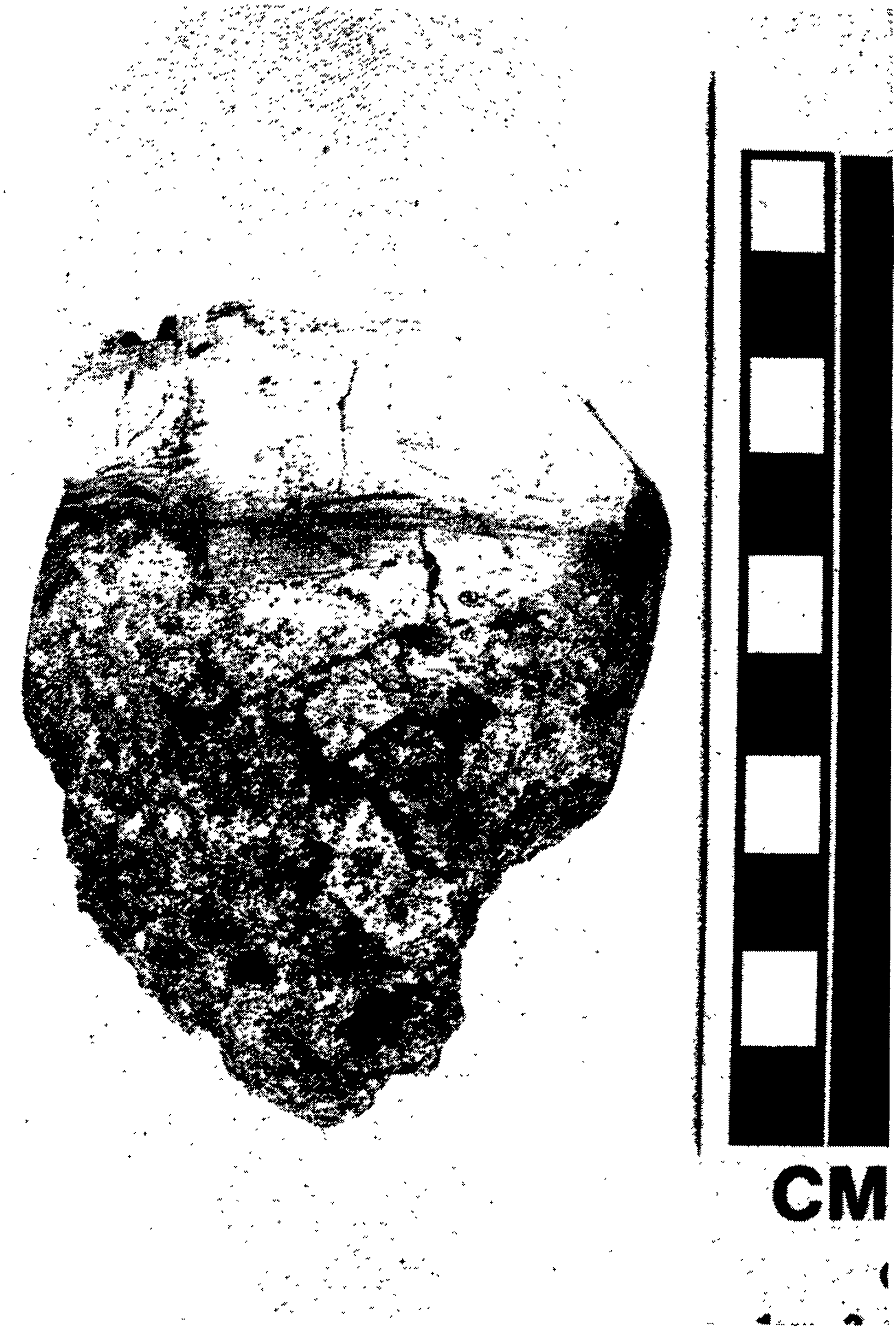

FIG. 7—Hand sample showing fireball layer overlying the ejecta layer at a K/T site near Beloc, Haiti. The 2 to 10-mm-thick, medium-grey, clay-rich fireball layer has been mixed with the overlying Tertiary limestone by fine-scale bioturbation. Analysis of samples of the fireball layer from this site show that it contains anomalously large amounts of the siderophile trace elements in roughly chondritic proportions. Large burrows mixed all three units present in the sample as evidenced by the lithologies exposed in the burrow cross sections. Burrowing of this type is common at the K/T boundary as preserved in marine sections (*e.g.*, Smit and Romein 1985).

(1990a) showed that the K/T crater would probably be ~1000 km from the Haitian sites, although an oceanic crater was still anticipated as the most likely provenance until the unaltered tektites were discovered by others as noted above. Subsequently, additional discoveries of two other proximal K/T ejecta deposits (*e.g.*, Smit *et al.* 1992, Alvarez *et al.* 1992) allowed a potential location to be predicted for the K/T crater. Hildebrand and Stansberry (1992) presented the results of applying this technique to the K/T boundary ejecta. Figure 8 shows the predicted location (using just the three most proximal sites), which is on the Yucatán platform north of the coastline of the Yucatán Peninsula. This location is also just north of the Chicxulub crater which is probably the K/T crater as discussed below. The validity of this solution is confirmed by adding constraints from the more distal K/T ejecta localities. The gravity and magnetic fields on the Yucatán Platform are known well enough to rule out any other possible candidate structure besides the Chicxulub crater in this area (*e.g.*, gravity anomaly map of North America 1988). Also the McGetchin *et al.* ejecta-scaling relation accurately predicts the ejecta-layer thickness variation across an observed range of five orders of magnitude as shown in figure 9. Least-squares fitting of the six "best" K/T ejecta localities yields a crater diameter of 178 km for a crater at Chicxulub's location; using all the meaningful data yields a crater diameter of 196 km (Hildebrand and Stansberry 1992). For comparison, the observed crater diameter is 180 km based on its gravity signature (Hildebrand *et al.* 1991). Furthermore, the calculated volume of the Chicxulub ejecta matches that of the Chicxulub crater (Hildebrand, 1992).

The discovery of the Haitian ejecta layer allowed major advances in K/T and impact cratering studies resulting in a near consensus on the region of the K/T impact and leading to discovery of unaltered K/T tektite glass. Knowing the region of impact led within a year to the discovery of the Chicxulub crater as discussed below.

6. The Chicxulub Crater. I thought that the debate concerning the postulated impact at the K/T boundary (Alvarez *et al.* 1980) would be resolved by the discovery of the impact site and the thick proximal deposits of the impact (*e.g.*, Hildebrand and Boynton 1990b) and the Chicxulub crater on the Yucatán Peninsula seems to be the K/T impact crater (*e.g.*, Hildebrand *et al.* 1991). However, Officer *et al.* (1992) have challenged its identification as a crater and still argue that no good evidence of an impact at the K/T boundary has been found, preferring a volcanic model. Also, it is not clear that the debate is over in the larger geological community, although much additional supporting research is now being published. Given that additional evidence is still being published (and that some proprietary data have not yet been released for publication), and that it takes time for due consideration, it may be that the larger geological community

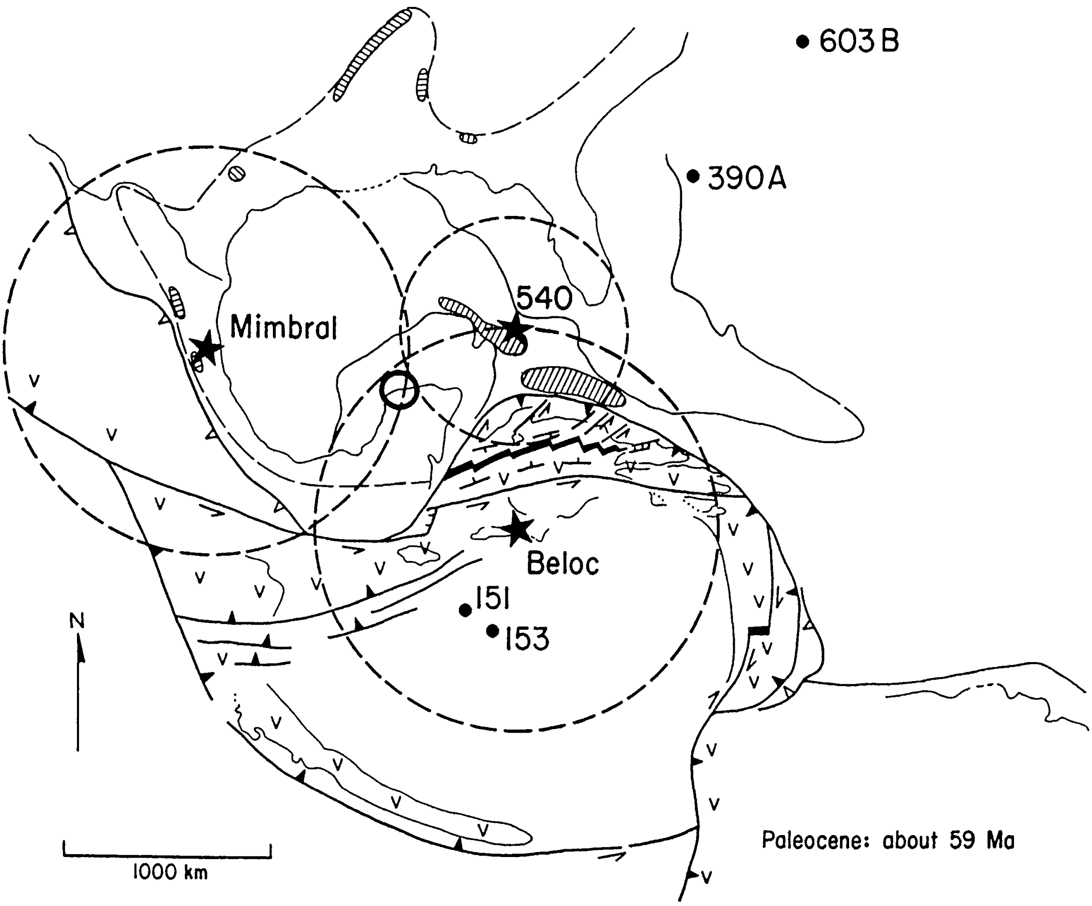

FIG. 8—Location of K/T crater from distance/ejecta thickness scaling. Modified from Hildebrand and Stansberry (1992) and a plate tectonic reconstruction of the Caribbean region near K/T time by Pindell and Barrett (1990). Bold lines show fault zones between plates with relative motions indicated by arrows and triangles. Solid triangles indicate subduction zones; open triangles indicate thrusting. Vees indicate subduction-related, island-arc volcanism. The diagonal-ruled areas show regions where possible impact-wave deposits occur. The lightly dashed line shows the paleoshoreline on the North American continent. Impact-wave deposits also occur at DSDP sites 151, 153, and 603B, which are shown as dots. Stars mark the positions of the 0.5 to 2.5-m-thick K/T ejecta layers preserved near Beloc, Haiti, Mimbral, Mexico and D.S.D.P. Site 540 in the mouth of the Gulf of Mexico. A solid circle shows the ~180-km-diameter Chicxulub crater on the Yucatán platform. Heavily dashed circles show calculated distances to the K/T crater from the three proximal K/T ejecta localities using the scaling relation of McGetchin *et al.* (1973) and assuming a crater diameter of 180 km.

will now accept the impact origin for the boundary layers. In 1984 only 45% of geoscientists felt that an impact occurred at the K/T boundary (Hoffman and Nitecki 1985). The questions of "Did the impact cause the extinctions?" and "Did a mass extinction occur at the K/T boundary?" are related but separate points.

The probable K/T crater lies buried on the northern Yucatán Peninsula (figures 8 and 10). Approximately 200-km-diameter, circular anomalies in both magnetic and gravity fields with associated breccias and andesitic igneous rocks at depth have been known for decades on the northern margin of Mexico's Yucatán Peninsula. They had been generally interpreted as representing a volcanic centre (*e.g.*, Lopez Ramos 1975). However, they were independently suggested possibly to represent a large buried crater to Petróleos Méxicanos by R. Baltosser (personal communication) in 1968 and G. Penfield (proprietary industry report) in 1978. Because proprietary data sets acquired by Petróleos Méxicanos in the course of petroleum exploration were never released for publication, the conventional view that the rocks in the area were volcanic persisted, although Penfield and Camargo (1981) were allowed to present the results of modelling the geophysical data in 1981 (together with the suggestion that the structure might be the K/T boundary crater). Some in the K/T community considered Penfield and Camargo's suggestion that the structure was possibly a crater at that time (*e.g.*, W. Alvarez personal communication) but a lack of samples to study for shock metamorphism and the conventional view of it as volcanogenic led to an end of these investigations. Eventually a version of the gravity data was published and some samples from some of the oil wells drilled in and near the structure were found, allowing Hildebrand *et al.* (1991) to describe geophysical, stratigraphic, and petrologic evidence establishing that this structure is indeed a large impact crater of possible K/T age. Despite some substantial initial opposition (*e.g.*, Sharpton *et al.* 1991, Marin *et al.* 1992a) additional groups of researchers have published evidence in support of this contention (*e.g.*, Pope *et al.* 1991, Hildebrand *et al.* 1992, Quezada Muñeton *et al.* 1992, Swisher *et al.* 1992, Sharpton *et al.* 1992) and it has become the working model for many in the K/T community.

The occurrence of the crater in the midst of the Yucatán carbonate platform and its subsequent burial in a region of tectonic quiescence has allowed an extraordinary degree of preservation of its gravity and magnetic signatures. Bouguer gravity data from the Gravity Anomaly Map of North America (1988) show a ~180-km-diameter, circular, three-ringed, radially-symmetric, ~30 mGal negative field anomaly (figure 10). A centre (89.60°W, 21.27°N) 10 km east of Progreso near the two of Chicxulub Puerto best fits the two internal concentric lows; the outer margin of the anomaly might be best fitted by a centre slightly to the northeast. (I named the crater Chicxulub because its centre occurs near this town and because I thought that using a Maya name to reflect the indigenous culture was most appropriate. Also, some translations of Chicxulub, "tail of the devil" or "sign of the horns" are somewhat allegorical. The name has stuck despite initial grumping that it was unpronounceable. No formal rules exist for naming craters.) A ~20-km-radius, twin-peaked, central high of ~20 mGal is surrounded by a well-defined concentric low with a best-fit radius of ~35 km. Another concentric low occurs at ~60 km radius. The gravity field anomaly is truncated to the north by an ENE-trending lineament which

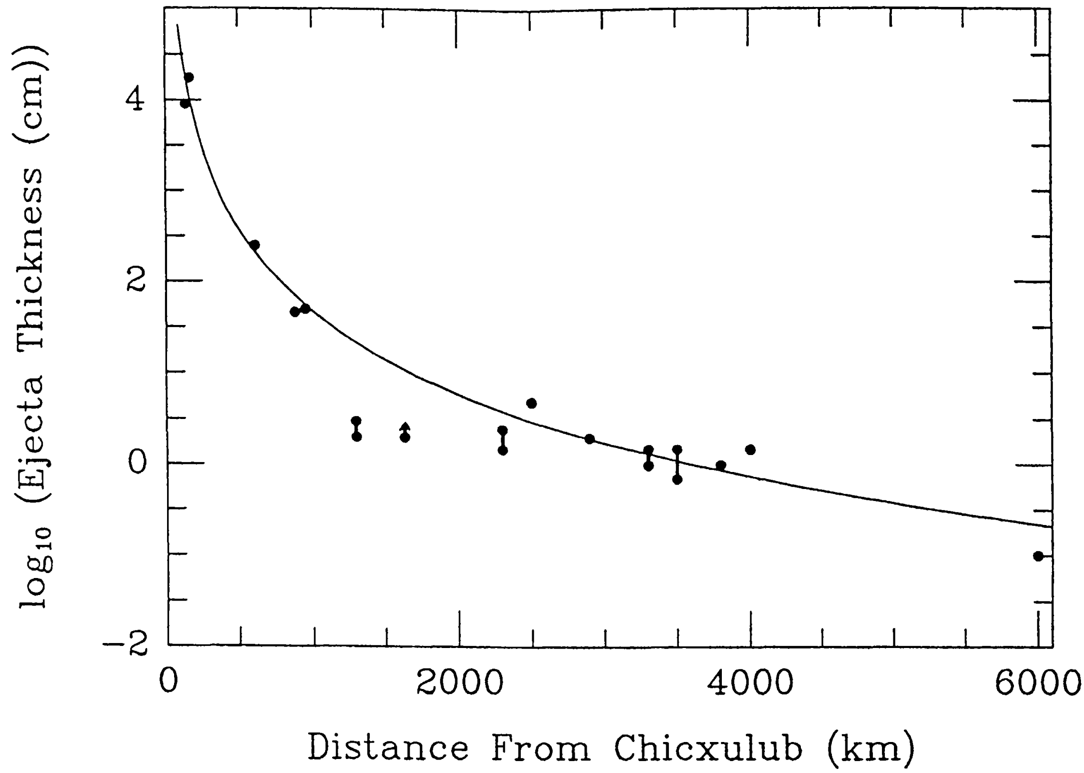

FIG. 9—Plot of observed versus calculated K/T ejecta thickness. Points represent observed ejecta thicknesses. The solid line represents the calculated ejecta thickness for the Chicxulub crater using the ejecta scaling relation of McGetchin *et al.* (1973). (Plot courtesy of J. Stansberry)

crosses the Yucatán platform north of the present coastline. A ~70 km-wide, negative anomaly trails ~100 km to the south from the southern margin of the circular gravity field anomaly. The circular structure of the anomaly is complicated near the northern-truncating lineament and the southwards-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 further, to ~45 km radius. The largest amplitude anomalies define a central zone ~20 km in radius which apparently corresponds to the central gravity high. An outer zone of weaker (5 to 20 nT) short-wavelength anomalies extends to a radius of ~105 km. The magnetic field anomalies extend to the north without significant disruption across the lineament which truncates the gravity field anomaly (Hildebrand *et al.* 1992). The central anomalous zone is slightly elongated in a NNW-SSE direction. Modelling of the magnetic field anomalies place the top of the magnetic source bodies at a depth of ~1100 m (Penfield and Camargo 1981). The outer margin of the zone of magnetic field anomalies is slightly irregular.

The stratigraphy within the geophysical anomalies and the adjacent Yucatán

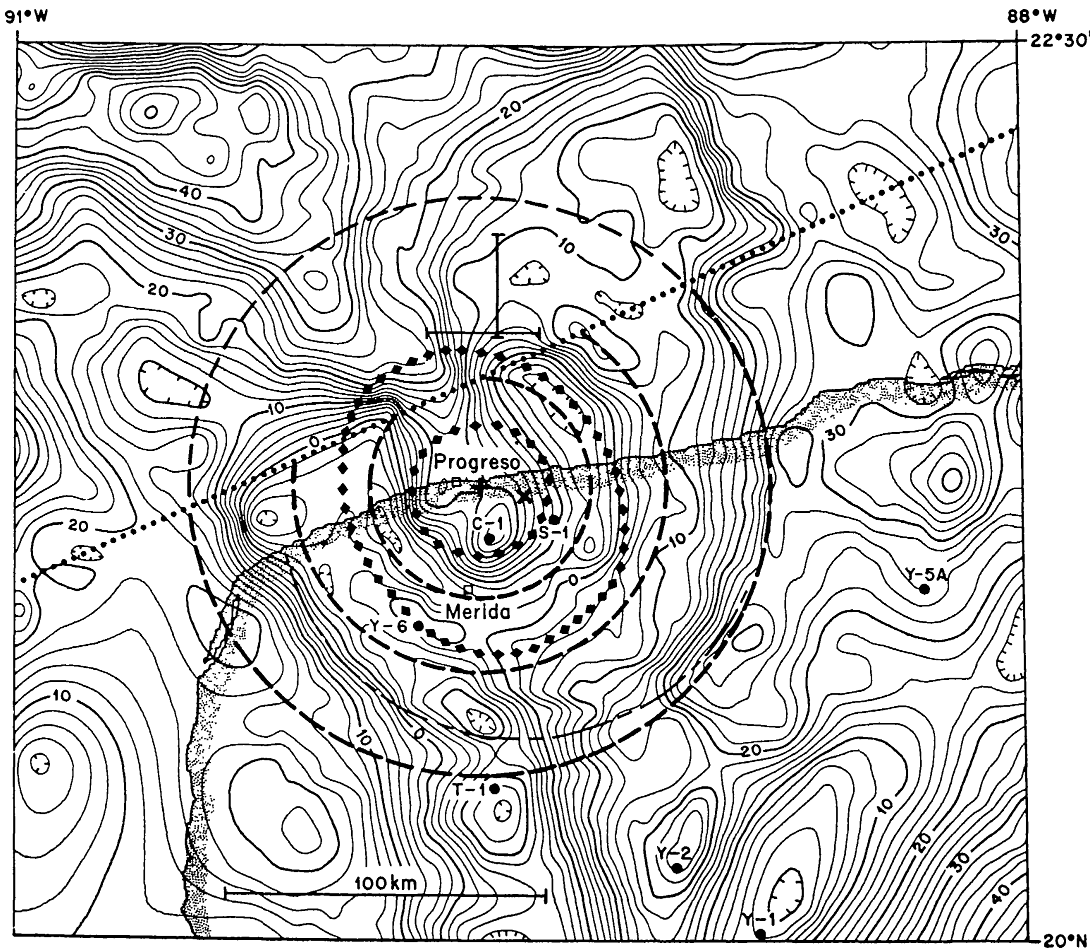

FIG. 10—Contour plot of Bouguer anomaly gravity data (from the Gravity Anomaly map of North America, 1988; contour interval = 2 mGal) covering the northwest corner of the Yucatán Peninsula, Mexico (Modified from Hildebrand *et al.* 1991). The outermost heavily-dashed circle shows the margin of a circular negative gravity anomaly; the two other circles show concentric lows within the negative anomaly, whose centre is indicated by a cross. The dotted line represents an ENE-trending regional lineament which truncates the anomaly. The dark solid lines near the top of the figure indicate the positions of two seismic reflection profiles. The alternating short- and long-dashed line indicates the position of the fracture-pattern ring described by Pope *et al.* (1991); its centre is indicated by an X. The rings of diamonds outline the edges of the two central zones of high-amplitude magnetic field anomalies. Small open circles indicate positions of exploration wells drilled by Petróleos Méxicanos: C-1, Chicxulub-1; S-1, Sacapuc-1; Y-1, -2, -6, Yucatán-1, -2, -6; T-1, Ticul-1.

carbonate platform is known primarily from petroleum exploration drill holes which record extraordinary deposits within the area outlined by the anomalies (*e.g.*, Cué 1953, Murray and Weidie 1967, Lopez Ramos 1975, 1983, Marshall 1974, Marshall *et al.* 1976, Weidie 1976, Weidie *et al.* unpublished cross section). The Yucatán platform is structurally uncomplicated with a platform sequence of nearly horizontal Early Cretaceous to Late Tertiary evaporites and

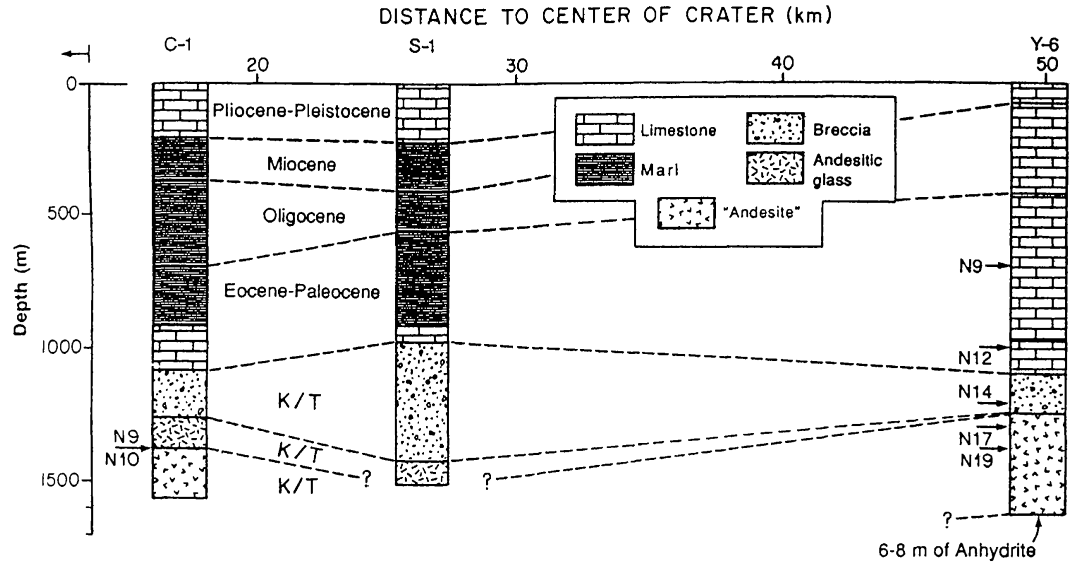

FIG. 11—Stratigraphic columns from the three deep wells in the Chicxulub crater (From Hildebrand *et al.* 1991); the patterns indicate the dominant lithologies. The vertical exaggeration is ten times. The drillholes are spaced according to their distance from the estimated centre of the structure. The unit ages at the base of the drilled section are K/T. Sample locations are shown by arrows.

carbonates overlying a poorly-known crystalline basement of metasediments and metavolcanics of probable Paleozoic age. The base of the Early Cretaceous carbonate sequence also contains abundant pyroclastics. In the northern part of the Yucatán Peninsula of the platform sequence is at least 3500 m thick. In this region the K/T boundary occurs at a depth of 300 to 500 m, excepting within the boundary of the geophysical anomalies, where it is depressed to ~1100 m in the three deep oil wells (1524 to 1644 m total depth) have been drilled within the margins of the geophysical anomalies. Figure 1 shows a compilation of the available stratigraphic information from these wells.

The ~1100-m-thick Tertiary sequence ranges from Pleistocene to Paleocene in age and is a flat-lying conformable sequence with no known significant stratigraphic breaks. The sedimentary facies and fauna reported from these wells indicate a deeper water environment than that found elsewhere on the platform (Marshall 1974). This together with unpublished seismic reflection data indicates the presence of a deep basin in the area in Early Tertiary time (Hildebrand *et al.* 1991). A circular basin is indicated by the circularity of the geophysical anomalies and circular patterns in the surface fractures in the region as noted by Pope *et al.* (1991). The circularity of fractures has strongly influenced groundwater flow in the region leading to the formation of a ring of sinkholes on the landward half of the crater. The Tertiary rocks are fossiliferous limestones and marls with minor shale, bentonite, and chert; pyrite and chert clasts also occur. The remainder of the wells penetrated unusual fine to coarse-grained breccias and andesitic igneous rocks. In wells C-1, S-1 and Y-6 limestone and bentonite breccias (containing Cretaceous fossils), 180, 445 and 150-m-thick respectively, are found with interbedded marls, shales, and sometimes dolomitic limestones. Thin intercalations of andesitic glass occur in the lower part of this unit in the first two wells; in Y-6 the unit is graded as though reworked by water. Thick units of andesitic glass underlie the breccias in C-1 (with minor interbedded tuffs) and S-1. The unit is 111 m thick in C-1 and S-1 bottomed in andesitic glass after intersecting 97 m. Cué (1953) showed the interbedded glass and tuffs in C-1 as a series of layers ranging from 10 to 30 m thick. Well Y-6 did not intersect any andesitic glass, but 380 m of microcrystalline andesitic rock is present. Well C-1 bottomed in 191.5 m of a similar unit containing abundant crystals of magnetite and occasional pyritic zones. Cué shows two distinct layers ~35-m-thick at the top of this unit. The Y-6 well bottomed in 6 to 8 m of laminated anhydrite, underlying the andesitic rocks.

These andesitic igneous rocks are found only in the three deep wells inside the circular zone of the geophysical anomalies, although several other drill holes have intersected this stratigraphic level in the northern Yucatán Peninsula and one of them, the Ticul-1 (T-1) well, is only 60 km from Y-6. Possible analogues to the limestone and bentonite breccias do occur in other holes as the upper most stratigraphy of the Cretaceous. For example, in well Yucatán-2 (Y-2), located ~135 km southeast of the anomalies' centre (figure 11), a unit of bentonitic, limestone breccia occurs from 240 to 330 m, (Weidie *et al.* unpublished cross section). Also, in well Yucatán-1 (Y-1), located ~170 km southeast of the anomalies' centre, from 265 to 440 m, is a unit of anhydrite interrupted by thick bodies of limestone breccia and cryptocrystalline limestone with interbedded thin layers of bentonite near its base (Lopez Ramos 1975). Both of these units are overlain by Paleocene limestones.

The stratigraphic succession reported from the three deep wells within the geophysical anomalies is typical of those observed for large complex craters (*e.g.*, Grieve *et al.* 1977). However, definitively establishing an impact origin for the structure required finding samples of the suspected impact melt and breccias to study for evidence of impact such as shock metamorphism. Because the wells were drilled for petroleum exploration, recovered samples were proprietary, and because of a fire at the sample storage warehouse, most recovered samples were lost. Fortunately, some samples were located which allowed the necessary proof of impact processes to be found (*e.g.*, Kring *et al.* 1991, Hildebrand *et al.* 1991, 1992). Subsequent to the publication of these results other samples were found thereby allowing independent confirmation of these results (*e.g.*, Swisher *et al.* 1992, Sharpton *et al.* 1992). Evidence of shock metamorphism is found in both the intracrater breccias and melt rocks in the form of shocked quartz and feldspar grains in samples such as Y6 N14 (figure 11). Figure 12 shows a shocked quartz

FIG. 12—A 0.32 mm shocked quartz grain from petroleum exploration well Yucátan 6 drilled inside the Chicxulub crater. This grain shows at least 8 sets of planar deformation features when rotated; two strong sets and part of a third set are visible in this orientation. The shock lamellae are decorated with inclusions. Photographed in cross-polarized light.

grain from this sample. The planar deformation features (PDF) typical of shock metamorphism (*e.g.*, French and Short 1968) have been studied in separated grains and in thin section on petrographic microscopes. Orientations of the PDF are as found at other known impact craters and artificial shock environments such as nuclear device test sites. X-ray diffraction Debye-Scherrer studies confirm crystal-lattice damage in the shocked grains. Occasional shocked quartz grains are also found as xenocrysts in the Y6 N17 andesitic melt rock sample. This sample shows evidence of super-heating (a characteristic typical of impact-melt rocks but lacking in volcanic rocks) in the form of reaction rims around partly digested inclusions in the melt. The composition of the melt rock is also not on any volcanic trend (Kring and Boynton, 1992) which is another characteristic of impact-melt rocks whose composition reflects that of the rocks targeted by the impact.

Evidence of shock metamorphism was also found in samples from a deposit ~50 km outside the crater. A largely altered melt clast containing abundant shocked quartz and feldspar grains was found in the 90-m-thick polymict boundary breccia which occurs in well Y-2 (Hildebrand *et al.* 1991). This breccia also contains uncommon shocked grains in the carbonate clast breccia which predominates in this stratigraphic unit. These features indicate that this breccia probably represents the crater's proximal ejecta blanket and its thickness matches the prediction of an ejecta scaling relation as noted above.

The age of the crater's formation was a point of contention because of conflicting stratigraphic age constraints. Most of the biostratigraphic work was done for proprietary petroleum exploration so that detailed information was not available leading to some uncertainty regarding the validity of the studies. Additionally this work was done before the more precise current biostratigraphic definitions of the K/T boundary were formulated so that some uncertainty would exist in any case. As discussed by Hildebrand *et al.* (1991) the occurrence of the crater's ejecta at the K/T boundary in well Y-2 (Weidie *et al.* unpublished cross section) indicated a K/T age for the impact event. However, a limestone unit 60 to 170 m thick of Late Cretaceous age had been reported inside the Chicxulub crater overlying the impact breccias (*e.g.*, Lopez Ramos 1975). If the latter report were valid then the impact would have predated the K/T boundary. Hildebrand *et al.* (1991) tested the age assignment for this overlying limestone unit by sending one sample (Y6 N12) to G. Keller and W. Sliter who independently assigned the sample a Late Paleocene (P3) age. This indicated that the overlying limestone was at least in part (and might be completely) Paleocene rather than Late Cretaceous age. Subsequently, Marin *et al.* (1992a) challenged this unit's reassignment to the Paleocene on the basis of additional unpublished proprietary biostratigraphic work from the other two deep wells which intersected this unit and argued for an older age of impact during the Late Cretaceous. This age uncertainty was apparently resolved by Swisher *et al.* (1992) who reported radiometric age dating results using the $^{40}Ar/^{39}Ar$ method on a sample of glassy andesitic melt rock from the C-1 well (C1 N9). Swisher *et al.* determined an age of 64.98±0.05 million years for the Chicxulub melt rock which is the same as they found for the ages of the K/T tektites found at Beloc (Haiti) and Mimbral (Mexico) of 65.07±0.10 million years. Therefore the age of the Chicxulub impact is the same as that of the K/T boundary within the precision of this dating technique, which is the most precise radiometric method currently available. These results have established the age of the crater as probably at the K/T boundary although biostratigraphic study of new samples from the crater can potentially provide a slightly better constraint.

The Chicxulub crater is probably the K/T crater for reasons discussed above but an additional strong indication is that the composition of the K/T ejecta matches that of the rocks impacted at Chicxulub. The bulk composition of the dacitic to andesitic K/T tektites overlaps that of Chicxulub's melt rocks (*e.g.*, Hildebrand *et al.* 1991, Alvarez *et al.* 1992, Smit *et al.* 1992, Swisher *et al.* 1992). The Sm-Nd and Rb-Sr isotopic systematics of the Chicxulub Y6 N17 melt rock are also similar to those of the Haitian tektites although not an exact match

(Hildebrand *et al.* 1991, Premo and Izett 1991). Additionally, the high-Ca K/T tektites require derivation from a carbonate terrane (*e.g.*, Sigurdsson *et al.* 1991a, b, Blum and Chamberlain 1992) such as the platform carbonates overlying the crystalline basement as impacted at Chicxulub. Finally, the high S content of some Haitian tektites, which were apparently derived from a sedimentary source based on their $^{34}S/^{32}S$ isotopic composition (Sigurdsson *et al.* 1992b), can be provided by the sulphate-bearing gypsum and anhydrite units interbedded with the carbonate rocks on the Yucatán platform (*e.g.*, Izett 1991, Sigurdsson *et al.* 1991a).

So the size, location, age and impacted-rock compositions of the Chicxulub crater match the source-crater requirements derived from the K/T boundary ejecta indicating that Chicxulub is the K/T crater.

7. Extinction Mechanisms. Since the evidence of an impact at the K/T boundary first began to appear, many impact-induced extinction mechanisms have been suggested; Wolbach *et al.* (1990) gave a listing of the more plausible mechanisms. Many different environments were affected and different extinction mechanisms were probably dominant in different environments; combined effects may also have been necessary to deliver the *coup de grâce* to some species. It is widely recognized that the rules for survival changed at the K/T boundary (*e.g.*, Jablonski 1986, Gallagher 1991), and this probably reflects the operation of extinction mechanisms which were not a factor before or after the boundary impact. Of interest here are mechanisms which would have global effects while recognizing that some mechanisms may have been more severe near the impact site so that refugia potentially existed at the most distant locales. Knowing that the Chicxulub crater is the K/T boundary crater allows more accurate modelling of these extinction mechanisms and has provided two new ones (as discussed below). The most significant fact to consider concerning the extinction capability of a large impact like the Chicxulub impact, relative to that of any known solely terrestrial process such as volcanism, is the tremendously greater energy release of a large impact as previously noted by Grieve (1982). The formation of a crater of Chicxulub's size ($\sim$180 km diameter) released $\sim 10^{25}$ joules of energy using a scaling relation of Schmidt and Housen (1987) on a timescale of one minute. This quantity of energy is equal to all the energy released by the total heat flux of the Earth ($\sim 3.5 \times 10^{13}$ W, Turcotte and Schubert 1982) in ten thousand years. Assuming that subaerial volcanism releases $\sim$2% of the Earth's total heat flow, the impact energy is equal to all the energy released by terrestrial volcanoes in five hundred thousand years. In the case of the eruption of the Deccan Traps, which is often suggested as the volcanic event responsible for the K/T extinctions (*e.g.*, Courtillot *et al.* 1990), the rate of energy release was $\sim 10^{12}$ times slower than the release rate for the Chicxulub impact although the total energy released was similar (Hildebrand 1992). The tremendous quantity of energy deposited on the Earth by the Chicxulub impact is sufficient to change the global terrestrial environment far more and far faster than that of any known terrestrial process. The only known mechanisms for altering the terrestrial environment which are similarly energetic are astronomical such as abrupt changes in our Sun, the close passage of another star (very improbable) or a nearby supernova. The extinction mechanisms discussed here are darkness and cold, acid rain from devolatized sulphates and oxidized atmospheric nitrogen, a thermal pulse from re-entering ejecta, and greenhouse warming from increased atmospheric CO_2.

Alvarez *et al.* (1980) proposed that the dominant agent of extinction was a globe-encircling dust cloud which blocked sunlight and left the world in cold and darkness for several years. Models of dust-settling (*e.g.*, Toon *et al.* 1982) have since established that the duration of the period of darkness would be limited to a period less than six months long (a two to three month duration would be most likely). Their climate models indicate that continental interiors would have cooled to below freezing for a similar length of time. In this scenario photosynthesis would collapse, leading to a breakdown of the food chain with extinction of higher animals because of a lack of food. This scenario is evidenced by the global occurrence of the K/T fireball layer. The layer was originally composed at least in part of fine-grained material, and therefore deposited slowly, because soot, a very fine-grained component of the layer, peaks in abundance in it (Wolbach *et al.* 1988, 1990, Hildebrand and Wolbach 1989). However, it is not clear to what extent it was responsible for the extinctions observed at the K/T boundary. The K/T mass extinction is one of the largest found in the Phanerozoic (*e.g.*, Sepkoski 1982), but impacts of sufficient size to distribute an opaque dust cloud globally occur with much greater frequency than mass extinctions of K/T magnitude (*e.g.*, Gerstl and Zardecki 1982). If dust clouds alone caused mass extinctions then the latter should be much more common than observed in the geologic record, implying that darkness and cold were not the dominant extinction mechanisms at the K/T boundary. Alternatively, modelling of the effects of darkness by Milne and McKay (1982) suggest that such a global darkening could cause the extinction of marine plankton.

Acid rain from impact-induced oxidation of atmospheric nitrogen has been suggested as an extinction mechanism (*e.g.*, Lewis *et al.* 1982, Prinn and Fegley 1987, Zahnle 1990). In these studies impact energy was assumed to couple to the atmosphere through the impact fireball and reentering impact ejecta. Lewis *et al.* (1982) advocated acid rain as a K/T extinction mechanism in the marine realm on the basis of selectivity of extinctions of marine organisms. In this scenario a sufficient fluence of acid rain would lower the pH of the mixed surface layer of the ocean to a point where organisms would die, possibly by dissolving their calcareous shells. Knowing the size of the crater allows comparatively well-constrained estimate of $\sim 10^{25}$ joules to be placed on the energy dissipated by the impact as noted above. This impact energy estimate is at the high end of estimates employed in the models of NO_x production implying that NO_x production by atmospheric processing was probably of sufficient magnitude to produce a lethal acid rain pulse.

Another source of acid rain has been independently suggested by many researchers (*e.g.*, Brett 1992, Hildebrand 1992, Perry *et al.* 1992, Sigurdsson *et al.* 1992) since the Chicxulub crater has been found. The stratigraphic sequence on the Yucatán bank impacted at Chicxulub included a significant fraction of gypsum and anhydrite evaporites (Lopez Ramos 1975). Impacting these rocks probably yielded SO_2 by the shock devolatization process based on the studies of other volatile-containing minerals, although apparently no experimental shock studies have been done with sulphates. The sulphates constituted $\sim 10\%$ of the stratigraphic sequence impacted at Chicxulub based on the proportion found in the pre-Tertiary section in the Ticul-1 well (Lopez Ramos 1975), the well closest to the outside of the Chicxulub crater (figure 11). Most of the wells to the southeast or east of the crater, such as Yucatán-1, -2, -4 and -5A, have even larger evaporite contents of $\sim 50\%$, suggesting shallower water depths or less oceanic circulation in those directions. Assuming that the sulphates will devolatize, and scaling to the CO_2-release model of O'Keefe and Ahrens (1989), $\sim 10^{19}$ g of SO_2 would have been released by the impact. This equals $\sim 10^{17}$ moles of SO_2 which is of the same order as the largest suggested NO_x production from oxidizing atmospheric nitrogen by the K/T impact. Therefore, the mass of SO_2 potentially produced by the Chicxulub impact would be sufficient to acidify the entire surface layer of the ocean independent of nitrogen-based acids derived from oxidizing the atmosphere. If this sulphate devolatization occurred it would make the Chicxulub impact particularly deadly.

Prinn and Fegley (1987) suggested that an acid-rain pulse would produce geochemical anomalies by leaching cations from subaerial environments and transporting them to buffered sinks such as estuaries. Subsequently Hidebrand and Boynton (1989b) reported finding mercury anomalies at the K/T boundary as predicted by the leaching model, lending support to the acid-rain hypothesis.

Melosh *et al.* (1990) suggested that the thermal pulse from a sky filled with re-entering ejecta could ignite forests globally and cause extinctions of land-dwelling organisms by broiling them alive. A prompt source of soot is indicated by the observation that the soot abundance peaks in, or immediately above, the fireball layer as noted above. Melosh *et al.* used a mass fluence of ~ 10 kg m^{-2} for the re-entering ejecta based on the observation of a uniform global thickness of ~ 3 mm for the fireball layer. Their model produced global thermal pulses of at least 50 kW m^{-2}, which is sufficient to ignite vegetation worldwide and cause mass mortality among exposed subaerial fauna. However, their choice of the fireball layer as a ballistically distributed layer, originally composed of large (~0.5 mm diameter) particles, seems unsupported by observations of this layer. Submillimetre-sized particles do occur in the fireball layer (*e.g.*, Smit and Klaver 1981), but they are typically preserved as a minor component at most sites. At one site described by Smit *et al.* (1992) the fireball layer does appear to be mostly spherules averaging ~0.2 mm diameter. Furthermore, material ballistically ejected from a crater typically falls off in thickness with a power-law relation (*e.g.*, McGetchin *et al.* 1973) rather than having a uniform thickness as observed for the fireball layer. As previously discussed, the ejecta layer at the K/T boundary does show a power-law thickness variation so the emplacement of the K/T ejecta layer is probably more relevant to the thermal pulse model of Melosh *et al.* (1990) than that of the fireball layer (Hildebrand 1992). Using the ejecta thickness scaling relation of McGetchin *et al.* (1973), and assuming the Chicxulub crater is the K/T crater, the ejecta layer thickness is theoretically greater than that of the fireball layer (~3 mm) to ~5500 km distance from the crater. Near the impact site at 1000 to 2500 km distances, the thermal pulse will be three to two orders of magnitude greater, respectively, than the global value calculated by Melosh *et al.* (1990), because the ejecta layer is that much thicker than the coarse component of the fireball layer near the crater (Melosh *et al.* did note that the thermal pulse would probably be much larger near the crater). At distances >10,000 km the total energy of the thermal pulse will be at least an order of magnitude less than that calculated by Melosh *et al.* because of the thinning of the ballistically distributed ejecta. This implies that the thermal pulse had a regional effect, suggesting that refugia existed far from the impact site for the types of organisms threatened by this extinction mechanism. The regional effect implies that the two continents adjacent to the impact site, North and South America, should have been burnt to the ground. However, the rest of the globe, with the possible exception of western Europe and Africa, should have been relatively unscathed.

O'Keefe and Ahrens (1989) proposed that a K/T-scale impact into a target covered with a layer of carbonates could lead to the shock devolatization of CO_2 in amounts greatly exceeding the current atmospheric inventory. The Chicxulub impact corresponds to their worse-case scenario, having an ~4-km-thick carbonate target (Penfield and Camargo 1991) and being of energy comparable to or greater than the cometary impact considered by O'Keefe and Ahrens (Hildebrand 1992). The CO_2 pulse of $\sim 10^{20}$ g would have a long residence time in the atmosphere because it is not condensable. The CO_2 would have to be removed by chemical processes, such as dissolution in deep ocean water or submarine silicate weathering, with timescales of 10^3 to 10^5 years (*e.g.*, Broecker and Peng 1982, Berner *et al.* 1983). While in the atmosphere this quantity of CO_2, which is ~50 times the current atmospheric inventory, would produce a severe and immediate greenhouse warming by as much as ~15°C leading O'Keefe and Ahrens (1989) to suggest this long-term heating as an extinction mechanism at the K/T boundary. The $^{18}O/^{16}O$-isotope record shows possible brief warming events (*e.g.*, Smit 1990) and generally unsettled climatic conditions after the K/T boundary (*e.g.*, Zachos and Arthur 1986) which have been interpreted as possible evidence of climatic change and the reorganization of ocean currents (in response to global warming) by O'Keefe and Ahrens and Smit *et al.* (1992).

7.1 Impact versus volcanism as an agent of mass extinction. As mentioned above, many researchers have advocated that volcanism, specifically the eruption of the Deccan traps, a flood basalt province generated by rifting of the Indian subcontinent ~65 million years ago, may have caused the K/T boundary extinctions. Massive volcanic eruptions, while deadly locally, are unable to duplicate some of the effects of a large impact such as the one that formed the Chicxulub crater. For example, basaltic volcanoes cannot produce the global opaque dust cloud or the widespread thermal pulse of the K/T boundary impact. More-catastrophic, felsic eruptions are also apparently unable to cause mass extinctions as Erwin and Vogel (1992) found no extinctions associated with the largest known examples of this eruption type. However, it has been argued that basaltic volcanism could have acidified the ocean, thus producing a mass extinction. Officer *et al.* (1987) advocated that, if a volume of basaltic lava equal to about ten times that of the Deccan basalts were erupted in just a 10,000-year span, then the associated outgassed sulphuric acid might be able to acidify the upper mixed layer of the ocean, thus causing the K/T boundary extinctions in the marine realm. However, Officer *et al.* (1987) had to neglect mixing the ~100-m-thick, upper wind-mixed layer with the deep ocean on a timescale of 50 years (Broecker 1974) to have even this extreme eruption rate (three orders of magnitude greater than the actual average eruption rate of the Deccan Traps) produce the necessary pH change. Thus, basaltic volcanism fails as an acidifying agent for the ocean and the calculation of Officer *et al.* reinforces the requirement that any extinction-causing pH change in the surface layer of the ocean be effected on a short timescale (*i.e.* on the order of ten years).

One proposed K/T boundary extinction mechanism has been thought to be uniquely generated by volcanoes and therefore a potential problem for any theory of impact-induced mass extinction. McLean (1985) suggested that the eruption of the Deccan Traps caused the K/T extinctions by outgassing large quantities of CO_2 at an average release rate which would increase the global mean rate of endogenic release of by 10 to 25%. McLean suggested the increased CO_2 content of the atmosphere and mixed layer of the ocean would have lead to a climatic warming and a debilitating pH decrease for planktonic organisms in the mixed layer. However, the similarly sized Chicxulub CO_2 release occurred in $\sim$30 seconds or a factor of 10^{12} times as fast as the Deccan eruption scenario of McLean. Thus, if increasing the atmospheric CO_2 content may cause a mass extinction, then the Chicxulub impact would have been much more catastrophic than the eruption of the Deccan flood basalts.

The K/T impact energy was released on a geologically instantaneous timescale so that no thermal or geochemical feedback mechanism was immediately able to buffer the lethal environmental changes caused by the impact and thereby protect terrestrial biota from them. Assuming that the Chicxulub crater is the K/T boundary crater, lethal effects caused by the energy released by its formation could well have produced the mass extinction observed at the K/T boundary. The thick carbonate/evaporite platform target apparently made the Chicxulub impact all the more deadly. If the target type contributed significantly to its lethal consequences then the Chicxulub impact may have been the deadliest to have occurred on the Earth since the beginning of the Cambrian Period ($\sim$570 million years ago). However, the as yet poorly resolved Permo-Triassic mass extinction (Erwin 1990) was even more severe than the K/T extinction. If it was caused by an impact it must have been an order of magnitude deadlier than the Chicxulub impact. A cratering event about ten times as energetic as Chicxulub would be consistent with the cratering record preserved on the terrestrial planets.

8. *Consequences.* Because the potential of asteroid and cometary impacts to degrade the terrestrial environment severely to the point of causing mass extinctions has been established, how should this change the way we look at our world? It has been argued that impacts may have caused many of the mass extinctions observed in the geological record (*e.g.*, Raup 1990) not just the one at the K/T boundary. Whether all these extinctions were caused by impacts remains to be demonstrated but, departing from the K/T paradigm, other extinction horizons have been studied for signs of impact with some positive evidence now appearing although the search has been slow to yield unequivocal data (*e.g.*, Orth *et al.* 1990, Bice *et al.* 1992, Wang 1992, Claeys *et al.* 1992). Studying extinction horizons much older than K/T time is more difficult because fewer exposures exist for study, the remaining exposures (being older) have typically been more disturbed by secondary processes, and the paleontological record of the extinction has not been as detailed at any one locality nor as well correlated globally. Nevertheless, because impacts of the same size as Chicxulub occur once every $\sim$100 million years (*e.g.*, Grieve 1982) many of the mass extinctions may be impact induced. If this is true it implies that impacts have strongly influenced terrestrial biological evolution, culling terrestrial species episodically. Between impacts the Darwinian principles of survival of the fittest govern evolutionary success. We do not yet understand if evolution is hastened or retarded

by episodes of catastrophic mass extinction (we may have to examine the biological record on other planets with different impact rates to gain insights into this question) but the course of biological evolution on our planet has definitely been changed.

How likely is a environmentally dangerous impact likely to happen in the future? This question has been studied in the last decade (*e.g.*, Morrison *et al.* 1992) with the statistically based conclusion that impacts dangerous to our civilization occur at ~500,000 year intervals. The largest uncertainty associated with the prediction is knowing how large an impact is lethal globally (not the rate of impacts of a given size). Morrison *et al.* estimate that smaller impacts on the scale of the Tunguska impact of 1908 occur at ~300 year intervals. Although the population of Earth-crossing asteroids and comets is known well enough to estimate its size, most (~90%) of the individual objects have not yet been found, implying that an unheralded impact could occur at any time. Comparing the efforts made by our society to guard against other threats of lesser probability suggests that we should guard against this impact threat by funding telescopic searches for these objects but observational programs to date have been conducted for scientific purposes.

9. Conclusions. The K/T impact turned the Earth's surface into a living hell, a dark, burning, sulphurous world where all the rules governing survival of the fittest changed in minutes. The dinosaurs never had a chance.

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A. Hildebrand,
Geophysics Division,
Geological Survey of Canada,
Ottawa, Ontario,
K1A 0Y3

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