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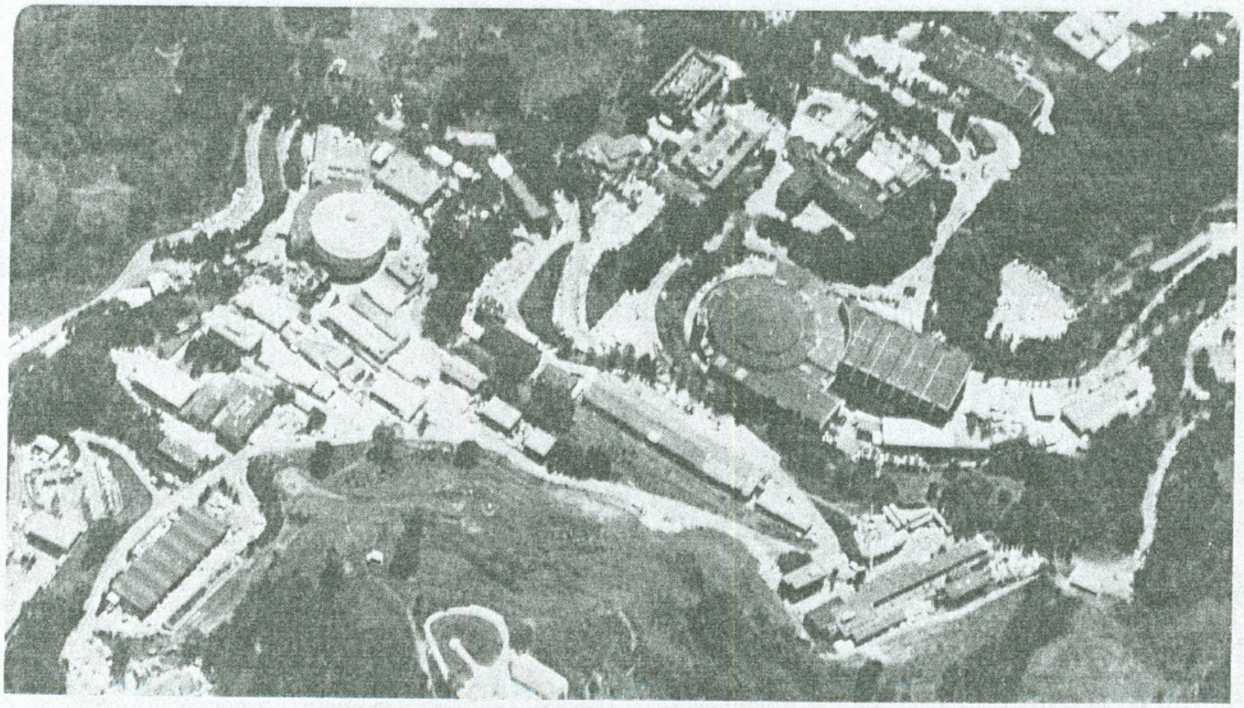

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(This article is based on a talk given at the Royal Swedish Academy of Sciences, Stockholm, December 11, 1986)

In this talk, I will describe the wealth of evidence that has forced my colleagues and me to conclude that the great mass extinctions, 65 million years ago, were caused by a large bolide impact on the earth. Bolide is a new word to most people, and it means any piece of solar system debris, such as a meteorite, asteroid, or comet nucleus. As I will show, the bolide responsible for the extinction of most of the then existing species, including the dinosaurs, was about 10 kilometers in diameter. My colleagues in all phases of this nine year study program[1] have been my son Walter, who is Professor of Geology at the University of California, and Frank Asaro and Helen Michel, who are nuclear chemists at the Lawrence Berkeley Laboratory, and experts in the technology of neutron activation analysis.

As one might guess, Walter introduced us to the Cretaceous-Tertiary, or K-T, clay layer, that separates the latest (Cretaceous) limestone deposits of the Mesozoic era, the age of reptiles, from the earliest (Tertiary) limestones of the present era. (Figure 1) After a good deal of discussion, Walter and I decided, incorrectly, that if we knew the iridium content of the clay layer, and of the rocks above and below it, we might learn how long the mysterious clay layer had taken to form. So we asked Frank and Helen to measure the iridium content of the one centimeter thick clay layer, and of the rocks above and below, and they brought us the data shown in figure 2. Iridium is very nearly the rarest of all

Fig. 1

CBB 790-16434

the stable elements in the earth's crust, but relatively speaking, it is ten thousand times more abundant in meteorites, and presumably, in all other bolides. The reason for this anomaly is well understood: when the bodies in the solar system condensed out of the original "solar nebula," the earth had the same elemental composition as the asteroids, meteorites and comets. But when the earth heated up, in its earliest stages, the molten iron preferentially scrubbed out platinum, iridium and the other siderophiles (iron lovers), and carried them down into the core. So the earth's crust is now severely depleted in iridium, compared to the smaller and therefore uncored objects such as meteorites, comets and earth-orbit-crossing asteroids.

Figure 2 shows time, or more accurately, stratigraphic height in the sedimentary rock increasing vertically, and iridium concentration increasing to the right. An unusual feature of the vertical scale is that it is linear for roughly the central third, which represents 30 centimeters. The lower third is logarithmic, going through 1 meter, 10 meters, 100 meters, down to 1 kilometer, while the upper third is also logarithmic, and goes up to 100 meters. These levels were measured in the Bottaccione Gorge, behind the medieval town of Gubbio, in northern Italy, where Walter had been doing field work on paleomagnetism for the past several years. We were all surprised to see the iridium concentration spurt up by a factor of 30, at the bottom of the clay layer, and then fall back more slowly, to its background value, which was the same in the limestones above and below the clay layer. When we measure it these days, it goes up by a factor of 300, because we no longer dissolve away the calcium carbonate before doing the assay.

In the summer of 1979, when Walter was collecting more rock samples in Italy, I set myself the task of identifying the origin of the iridium, under the "ground rules" that whatever was the source of the iridium must also provide a plausible basis for what I

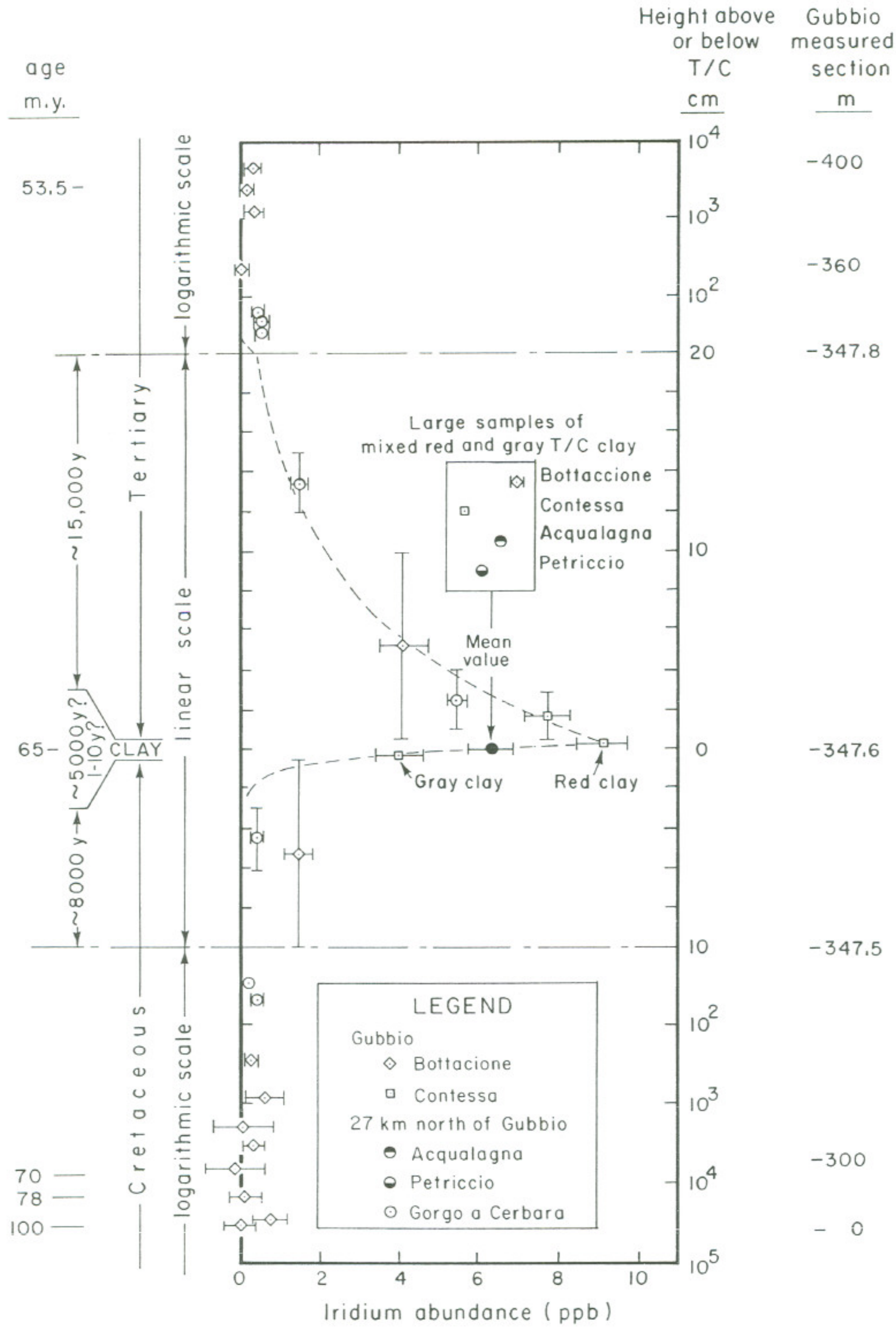

Fig. 2

XBL 7911-13250

called the "killing mechanism," to tie the iridium enhancement to the precisely coincident mass extinction of most of the life in the sea. That exact coincidence can be seen by any interested person who drives up the Gubbio gorge, equipped with a geologist's hammer and a hand lens. If he strikes a fresh surface of limestone with his hammer, and looks closely at that surface with his hand lens, he will see many small fossil shells called forams, in every field of view. That is true for rocks anywhere below the K-T clay layer. The prominent forams with a diameter of about 1 millimeter stop abruptly at the lower edge of the clay layer, indicating that they underwent an extinction at the very instant of geological time when the clay layer was deposited on the bottom of the sea. That is also true of the ammonites and several other major marine taxa of the Cretaceous period. Walter aroused my interest in the clay layer (Figure 1) when he told me that it was laid down at very nearly the time of the demise of the dinosaurs. (The slanting sediments shown in figure 1 were of course laid down horizontally on the sea floor, but were tilted as they were raised up to form the Apennines.) Walter said that no one knew what made the clay layer, or what, if anything, it might have had to do with the extinction of the dinosaurs, but we will soon see that the answers to both of those questions are now well in hand. But it was clear that the clay layer was causally related to the extinction of the local forams; if one tried to say that it was just a coincidence that the large forams disappeared within a millimeter of the bottom of the clay layer, it is easy to calculate the probability of such an accidental coincidence. If we remember that these most conspicuous forams are roughly constant in abundance from the clay layer downward for a kilometer, the odds against such a chance coincidence of two unrelated events is just the number of millimeters in one kilometer, or one million to one.

Frank has said that I tried out a new theory on him, once or twice a week, for six weeks, and shot each one down myself, before anyone else had a chance to do so. Finally, I tried the impact of a ten kilometer bolide, which in turn enveloped the earth in an opaque blanket of dust. While the dust fell in some months onto the ground, and into the ocean, it cut out the sun light, thereby stopping photosynthesis, so most of the animal life on earth died of starvation. And of course we now see the fallen dust as the worldwide K-T boundary layer. I'll describe a number of other consequences of the collision, all of which probably contributed to what has been called "the great dying."

We now know that it was extremely cold during the period of darkness,[2] so it was just as though all the animals had been transported to present day Antarctica. Emiliani, Kraus and Shoemaker[3] soon published a paper showing that after an impact in the ocean, the temperature would first go way down but would then increase as a result of the greenhouse effect, and the heating would be a major contributor to the killing mechanism. Perhaps the most important killing mechanism would derive from the shock-heating of the atmosphere, by the expanding fireball. It would give rise to the production of huge amounts of nitrogen oxides in the atmosphere, leading to highly acidic rain, and surface ocean waters with a pH so low as to dissolve the calcium carbonate shells of marine invertebrates. This important contribution came from a group at MIT (Lewis, Watkins, Hartman and Prinn).[4] I stress it here, because our paleontological colleague, Bill Clemens, recently discovered dinosaur fossils in Alaska,[5] and properly asked, "If dinosaurs could survive the darkness and cold of an Alaskan winter, why would they be bothered by the darkness and cold of your K-T scenario?" My best guess is that the answer lies in the rains, with their very high acidity—far beyond anything we now know as acid rain, plus the fact that it was warmer in Alaska during late Cretaceous times. Very recently, Dr. Prinn, of the MIT group said,[6] "Essentially pure nitric acid would be pouring over about 10% of the global surface in the first few months." Some paleontologists have been saying for the past few years that although the impact probably took place, it was only the straw that broke the camel's back. Pure nitric acid should make a fairly strong straw! I have no way to check the validity of the MIT statement, but it does come after four years of discussions of this scenario, in one of the most prestigious chemistry departments in the world, so I think it should be taken seriously.

I have just discussed the need for a plausible killing mechanism, but first of all, we must convince ourselves that it is reasonable to assume that the earth was hit, 65 million years ago, by a bolide that was 10 kilometers in diameter. (Mt. Everest is 8.8 kilometers high.) I'll soon show how easy it is to calculate the effective diameter of the bolide, but to do so, we need to know that the world-wide K-T clay layer is everywhere enriched in iridium. That was the first prediction of the theory, and as we see in figure 3, iridium enhancements have now been seen at about 75 locations throughout the world, in rock layers 65 million years old. The numbers in the boxes give the surface density of iridium, in billionths of a gram per square centimeter, and if we add up the amount on each square centimeter of the earth's surface, we find a total of about half a million tons of iridium. If we use the meteoritic iridium abundance of 0.5 parts per million, as representative of solar system debris, it is a simple exercise in geometry to calculate the diameter of a spherical bolide that brings in that much iridium, and the answer is close to 10 kilometers, which is the number we listed in our 1980 paper, and that hasn't been improved on. (Walter has suggested that the unevenness in the surface density, from place to place, can be attributed to the well known Rayleigh-Taylor instability of hydrodynamics, and that suggestion can be, but hasn't yet been tested.)

I will now show you that the impact of a 10 kilometer diameter bolide in the last 50

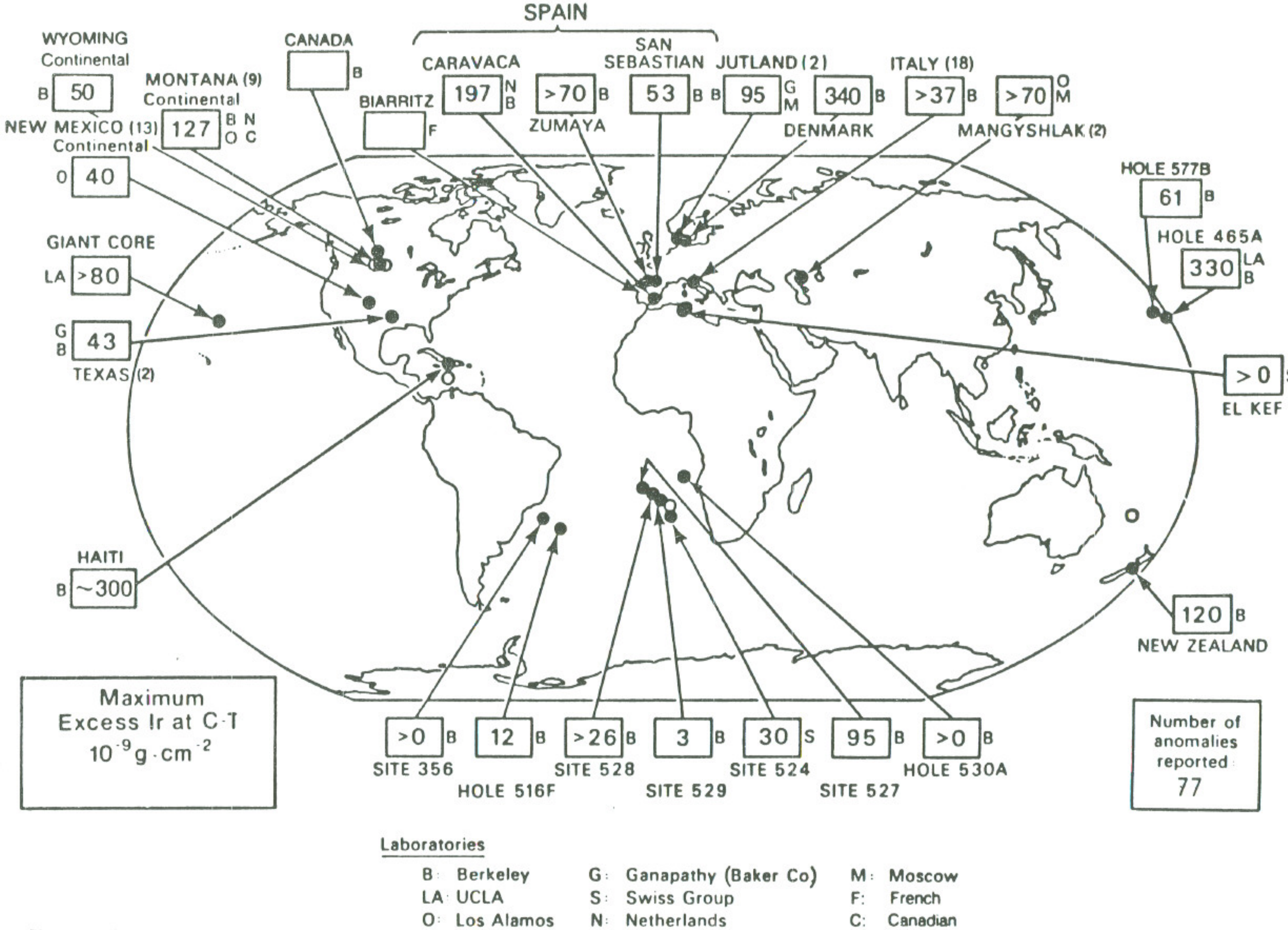
SPAIN
WYOMING
Continental
B 50
CANADA
B
CARAVACA
197 N B
>70 B
ZUMAYA
SAN SEBASTIAN
53 B
JUTLAND (2)
B 95 G M
340 B
DENMARK
ITALY (18)
>37 B
>70 O M
MANGYSHLAK (2)
MONTANA (9)
Continental
127 B N O C
NEW MEXICO (13)
Continental
O 40
BIARRITZ
F
GIANT CORE
LA >80
G B 43
TEXAS (2)
HAITI
B ~300
HOLE 577B
61 B
HOLE 465A
330 LA B
>0 S
EL KEF
120 B
NEW ZEALAND
Maximum
Excess Ir at C-T
10⁻⁹ g · cm⁻²
>0 B
SITE 356
12 B
HOLE 516F
>26 B
SITE 528
3 B
SITE 529
30 S
SITE 524
95 B
SITE 527
>0 B
HOLE 530A
Number of anomalies reported
77
Laboratories
B: Berkeley
LA: UCLA
O: Los Alamos
G: Ganapathy (Baker Co)
S: Swiss Group
N: Netherlands
M: Moscow
F: French
C: Canadian

Fig. 3

or 100 million years has a reasonable probability—rather than the one chance in a million that the iridium layer is unrelated to the foram extinction. Figure 4 was available to me in several pieces, in 1979.[7] It shows the average time between collisions with the earth, of bolides of different sizes over the enormous diameter range of ten orders of magnitude, which translates directly into 30 orders of magnitude in bolide mass. The data for this figure come from many sources, including lunar and terrestrial craters as well as tiny craters found on the surfaces of recovered spacecraft, plus telescopic observations of earth orbit-crossing asteroids. Eugene Shoemaker is recognized as the leading expert in this field. There is of course a good explanation for this simple power law, and it is called comminution—the process by which collisions of two objects produce smaller objects. Figure 4 describes the "integral spectrum" of objects orbiting the sun in the neighborhood of the earth, and it effectively "runs out of rocks" on the large diameter end near 20 kilometers. If we look at the numbers carefully, we see that the earth should be hit by a bolide 10 kilometers or greater in diameter, about once every 100 million years. So one should not be surprised to learn that the earth was hit by a 10 km bolide 65 million years ago.

I'll now speak briefly on how theories become accepted; most laymen feel that theories can be proved or disproved, but with very few exceptions, theories can't be proved, but only disproved. For example, Newton's still extremely accurate theory of gravity was disproved by Einstein's theory (called General Relativity), but Einstein's theory wasn't proved in that process—some new theory may prove that Einstein was wrong. So how do some theories gain nearly universal acceptance, when proofs are so rare? The answer is that every useful theory explains all known observations, and makes predictions, and if the predictions turn out to be true, particularly if some of them are very surprising, then that theory becomes an accepted theory, even though someone may later find that one of

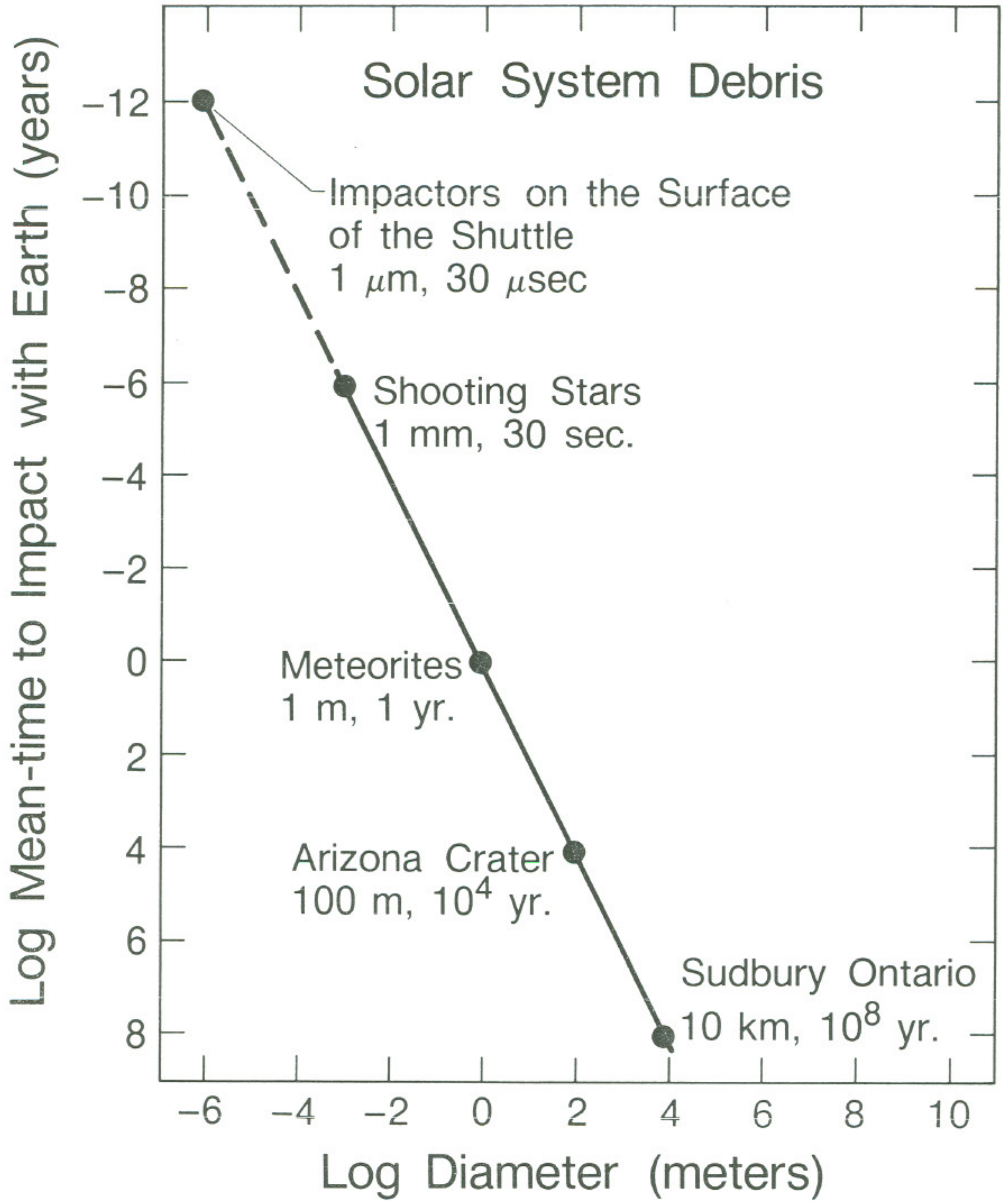

Fig. 4 XBL 8611-12757

its predictions doesn't correspond to reality, and thereby invalidates it. As an example of what I've called a surprising prediction, I'll mention Maxwell's kinetic theory of gases, which predicted that the viscosity of a gas would increase with temperature, which was counter to everyone's intuition, but which turned out to be true. (Viscosities of liquids decrease with increasing temperature.)

When our theory was first discussed in 1980 by the well-known paleontologist and essayist on the history of science, Stephen Jay Gould, he said he was favorably disposed toward it, and particularly liked the fact that it was testable. So I will spend much of the rest of this talk on the many tests that have been made of the theory—all of which have turned out to support it. Most of the tests have been of predictions we made as the theory was evolving, but some have been made of what are more properly called "postdictions." Confirmed postdictions are observations of phenomena that follow directly from the details of the theory, but which, either because of lack of foresight or faint heartedness, we didn't list as predictions, in our early papers. They are nonetheless predictions of the theory, so I won't stress their after-the-fact articulation; they test the theory just as well as formal predictions do. I have just discussed the first two tests of our theory: 1) that the Ir layer would be seen, worldwide and 2) that the bolide impact was a very probable occurrence, on a 65 million year time scale.

One of the comments several people made when they first saw the "iridium spike" was, "You've only looked for iridium near a known extinction, and sure enough, you found it there. But there are probably lots of iridium enhancements, all over the place, so the one you've found might not have much significance." Our theory said that since major mass extinctions are rare—only five in the past 550 million years, according to Dave Raup and Jack Sepkoski[8] (Figure 5)—iridium enhancements should also be rare. It has taken

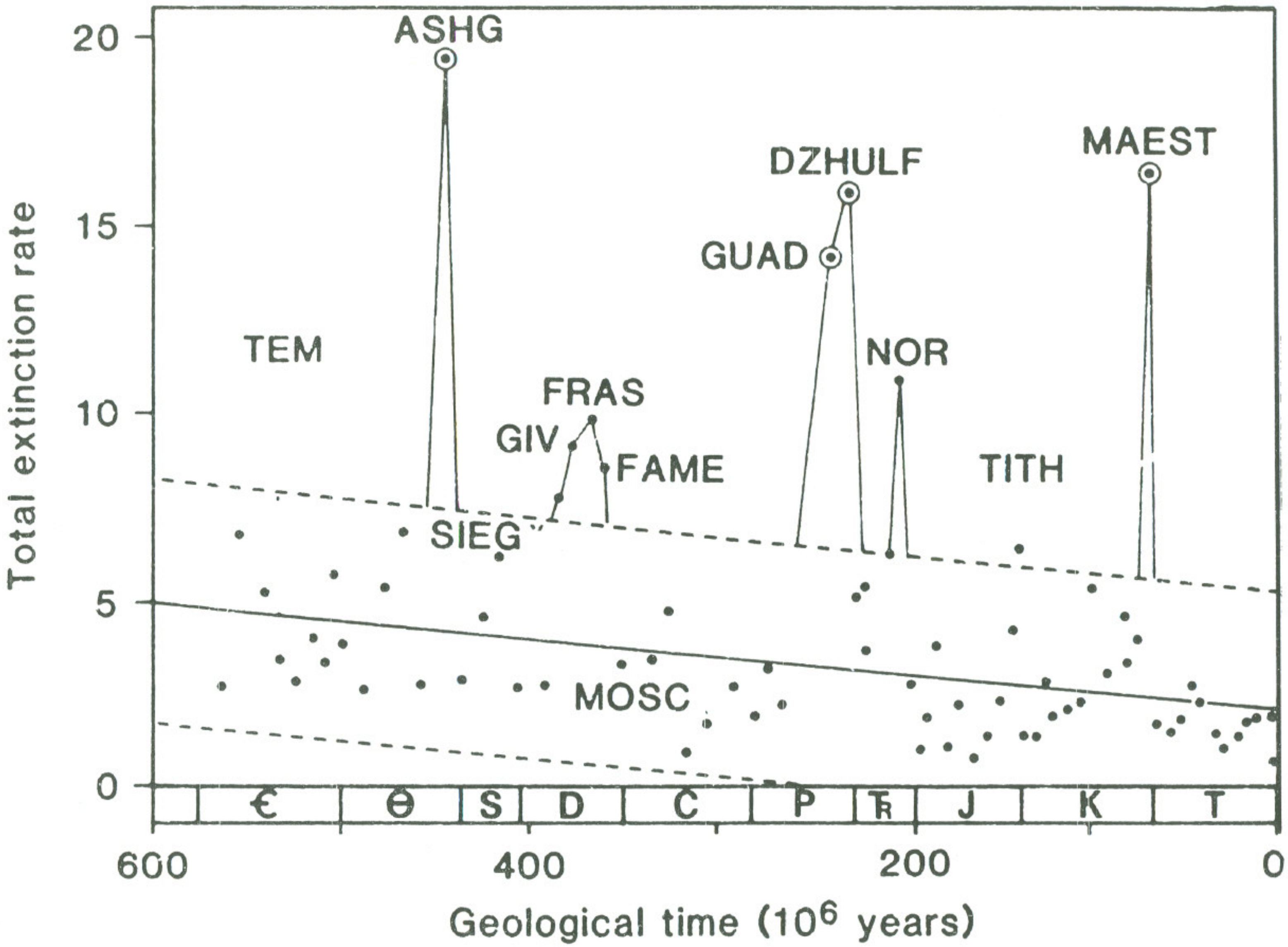

Fig. 5

XBL 829-9699

some time to confirm that third prediction, because until recently, iridium assays at the parts per trillion level have been both time consuming and expensive. Figure 6 shows the iridium level in one complete magnetic polarity zone ("29 R"), lasting about 500,000 years, 65 million years ago. These data are from Frank Asaro and Helen Michel, using a chemical separation technique to clean up the sample. You will note that the background level is quite constant at 12 parts per trillion. We now measure chemically-untreated samples, using a much more sensitive detector, designed by Frank and me (Figures 7a and 7b) . This new detector has just been equipped with an automatic sample changer, that lets us assay 500 samples over a weekend, with a detection limit of about 30 parts per trillion. Just how big an improvement this is can be seen from the fact that a few years ago, we could measure only a single sample to that level, over a weekend.

The difficulty of the measurements I am describing here can be appreciated by noting that when one identifies a particular person in the total world's population, he is operating at one in 5 billion, or 200 parts per trillion. We now work routinely with statistical errors of 1 or 2 parts per trillion, using no separation techniques to avoid contamination problems. Frank and Helen are so worried about contaminating their samples with iridium that when Frank recently visited Walter in Gubbio, he wouldn't touch the clay layer, for fear he would carry iridium on his hands back to Berkeley, where he could get false results on some new rock samples, by contaminating them with Italian iridium.

Figure 6 is part of the confirmation of prediction number 3, concerning the rarity of iridium enhancements. But before going on to a more extensive confirmation, I'll point out that an obvious prediction of the theory is that the K-T iridium enhancement would always be seen, worldwide, in the same magnetic reversal zone, number 29R. It was disturbing to us, in 1981, when two different groups reported that they had found the K-T fossil

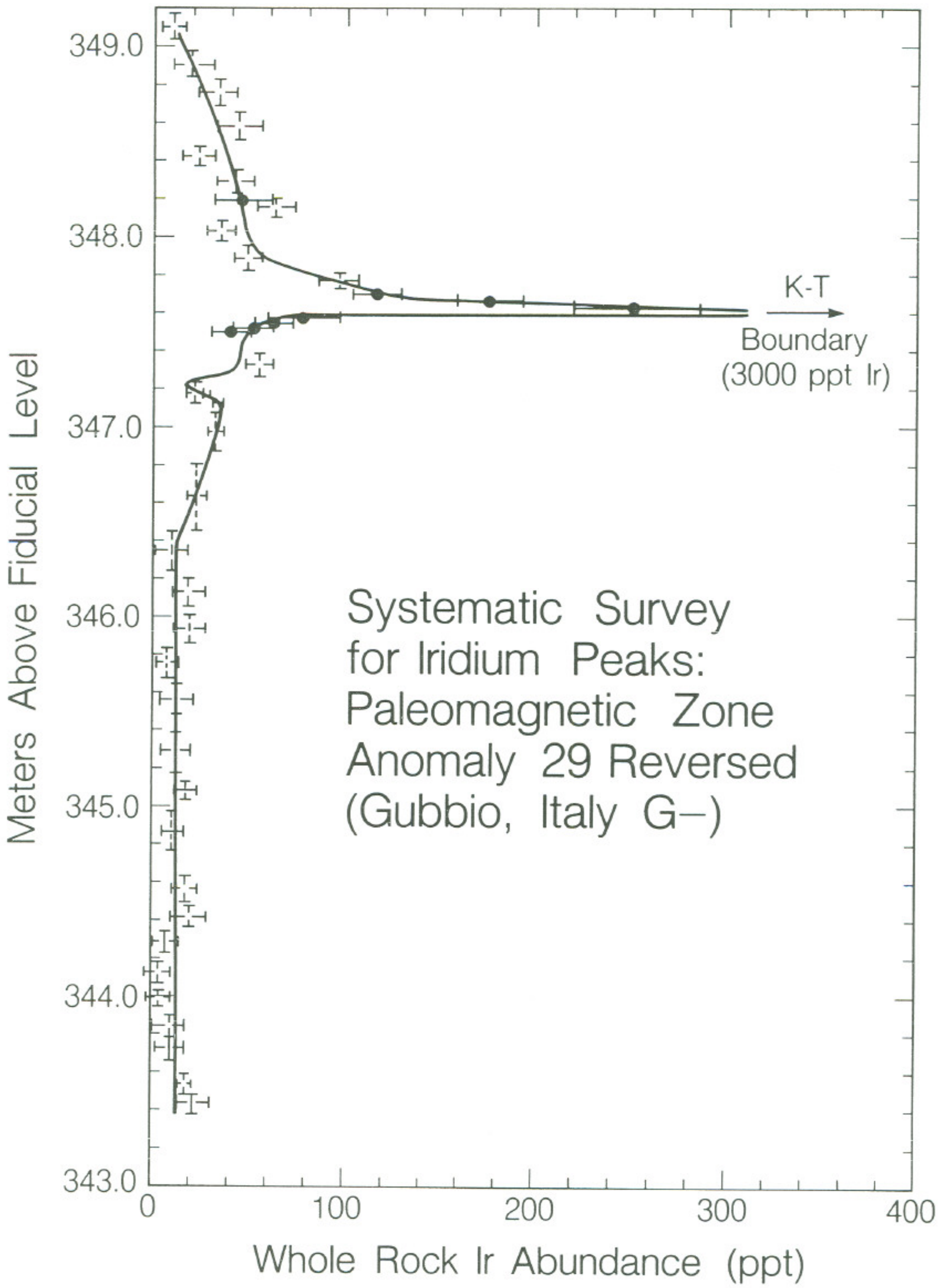

Fig. 6

XBL 864-10088A

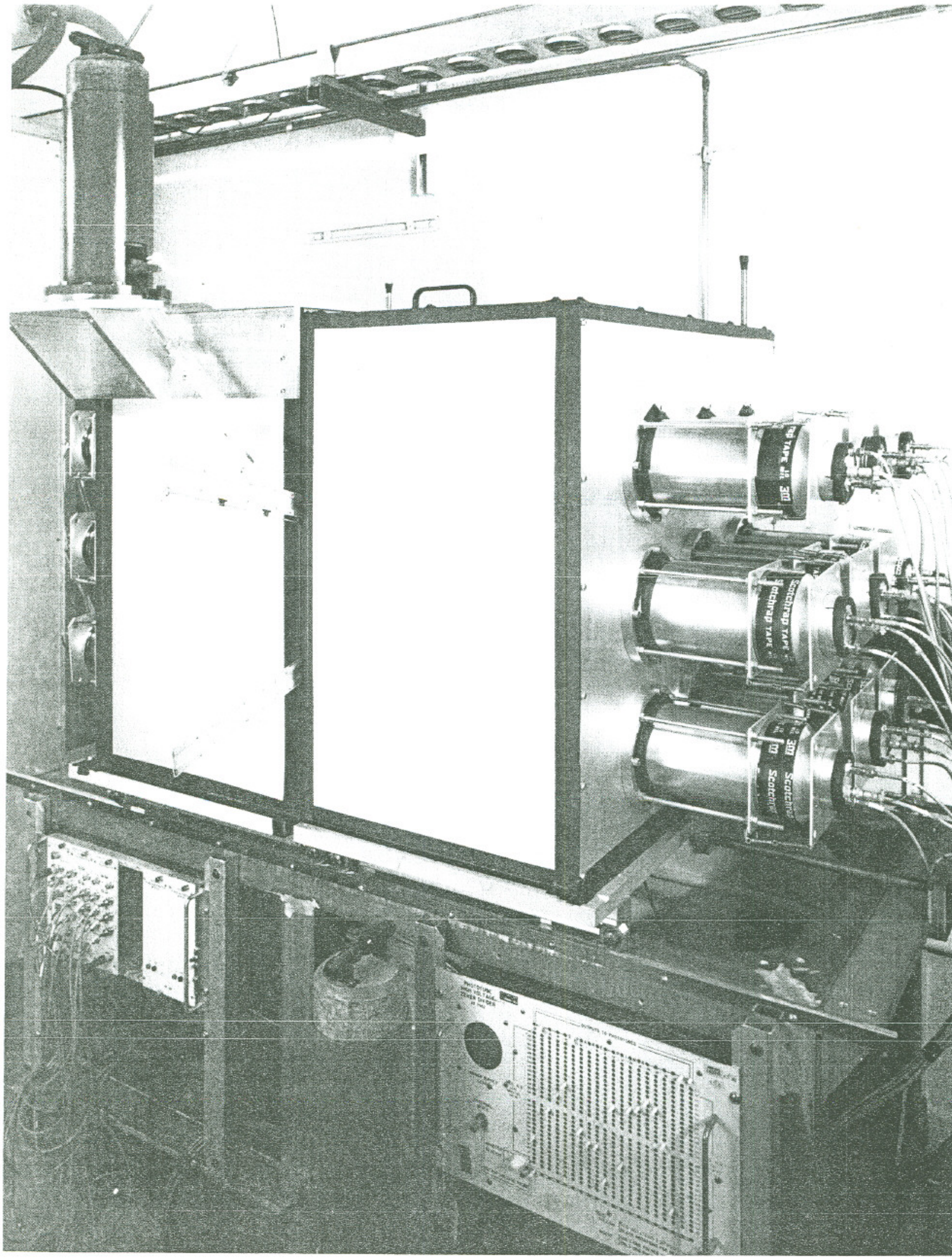

Fig. 7a CBB 860-9864

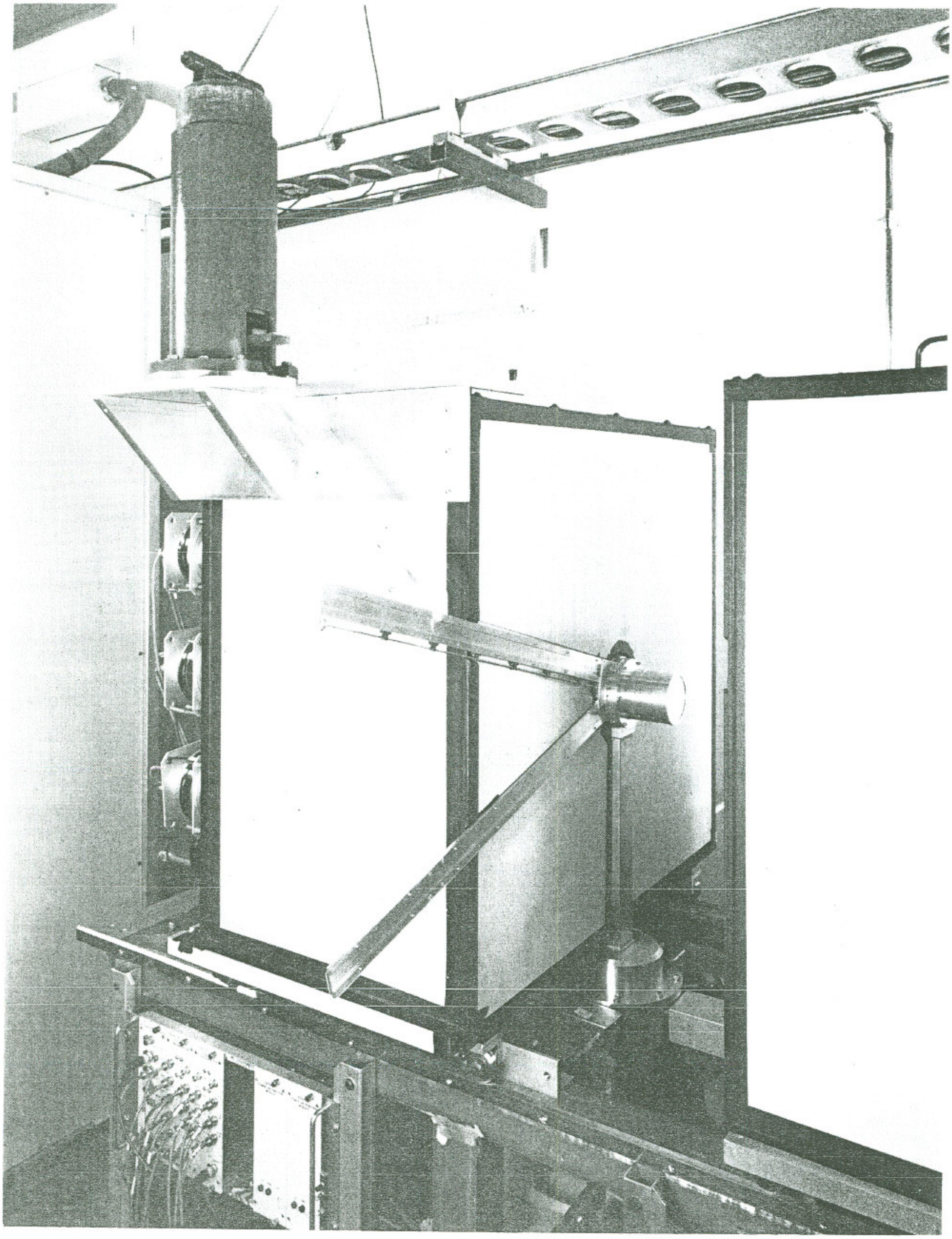

Fig. 7b

CBB 860-9860

boundary in a magnetic zone during which the earth's magnetic field pointed in its normal, rather than in its reversed direction. So we were pleased when it was subsequently shown that the K-T boundary in both instances had occurred in a reversed polarity zone, one of which was identified as 29R. I'll call this work the confirmation of prediction number four, that all the K-T iridium enhancements, seen worldwide, were simultaneously laid down.

We have now seen that on a time scale of a few hundred thousand years, large iridium enhancements are rare—there is only one in the half million years of the 29 R zone. But to answer those who originally felt such enhancements would be common occurrences, I'll now show you an interval of 34 million years, in which the K-T iridium spike is the only one visible. These new observations come from Frank Kyte and John Wasson,[9], and they were made on deep sea drilling cores from a part of the Pacific Ocean that has one of the slowest sedimentation rates I've ever heard of. They were of course chosen for that reason, so Kyte and Wasson could look at the longest interval of time, in the smallest number of samples. Figure 8 shows the results of Kyte and Wasson, in the period from 67 million years ago, to 33 million years before the present. The K-T iridium spike is the only obvious one showing, indicating that it was a most unusual event, for which the word unique might well be used. We will soon see that it can be dated as simultaneous with the extinction of the dinosaurs, to within the very small experimental errors, so we can then invoke Occam's Razor to say that they are causally related, and therefore simultaneous, in the geological sense of that word. (But more about this later.)

Another very important prediction of our theory was that (5), the iridium layer would be seen on sites that were not at the bottom of the sea, 65 million years ago, as all our first ones were, but were either on dry land or in regions covered by fresh water. Number five was important because there was an early tendency of some people to dismiss the notion

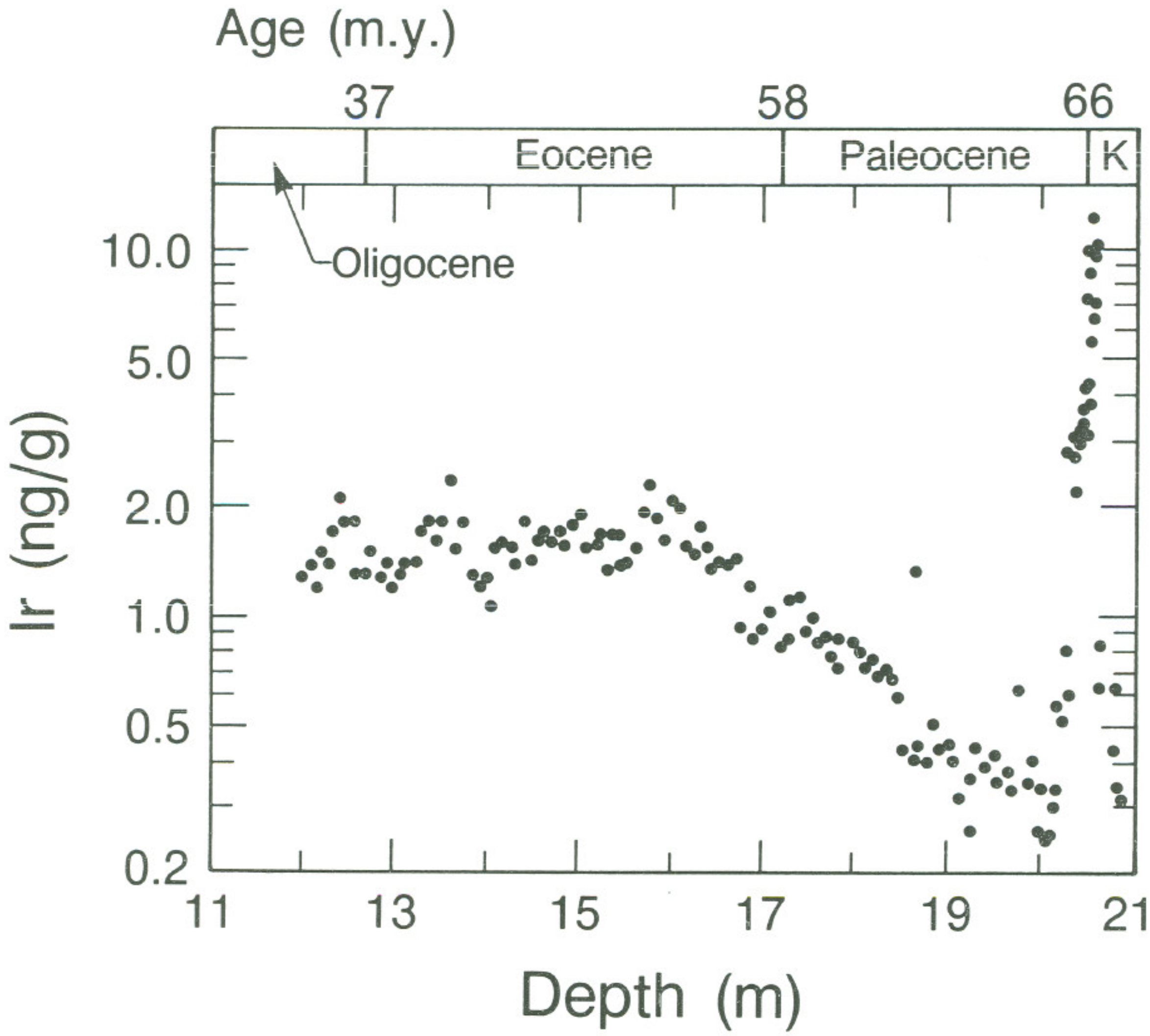

Fig. 8

XBL 8611-12758

of a large bolide impact, and substitute the idea that a sudden change in ocean chemistry had precipitated the observed iridium out of solution in the ocean. (But that explanation could be discarded if an iridium enhancement were to be found on a continental—non-marine—site.)

We were searching for iridium in the dinosaur-rich bad lands of Montana, in 1981, and hoped to find the first iridium enhancement on a continental site. But we lost that race to Carl Orth and his Los Alamos and U.S. Geological Survey colleagues.[10] They found the iridium, in drill cores from a well in the Raton Basin of New Mexico. And Carl's drill hole also confirmed another important prediction of the theory, that plants as well as animals did feel the effect of the bolide impact. We had been told by some of the best paleobotanists that the K-T extinction didn't extend from animals to plants. But it was central to our theory that the plants would also experience trauma, and even extinctions, and that can be listed as our prediction number 6. So we were pleased when Carl Orth and his associates published the data shown in figure 9. The ordinate is the depth of the samples in the well, below the surface, and on the left-hand half of the figure, we see the iridium concentration, increasing to the right. It increases by a factor of 300, the same as in our Italian sea floor sample, in a sharp spike, so the Orth group plotted that concentration on a log scale. As I just said, that confirms prediction number 5, and in a rather surprising fashion, if you remember that Carl Orth used a well in a continental New Mexico site, that extended down to the K-T horizon, simply because we had found an iridium peak on the face of a limestone cliff in the Apennines, that had been deposited on the ocean floor, at about the same time, 65 million years ago, and nearly half way around the globe. So it is clear that the ocean wasn't the source of the iridium.

If you now look at the right hand side of figure 9, you'll find out why I consider this

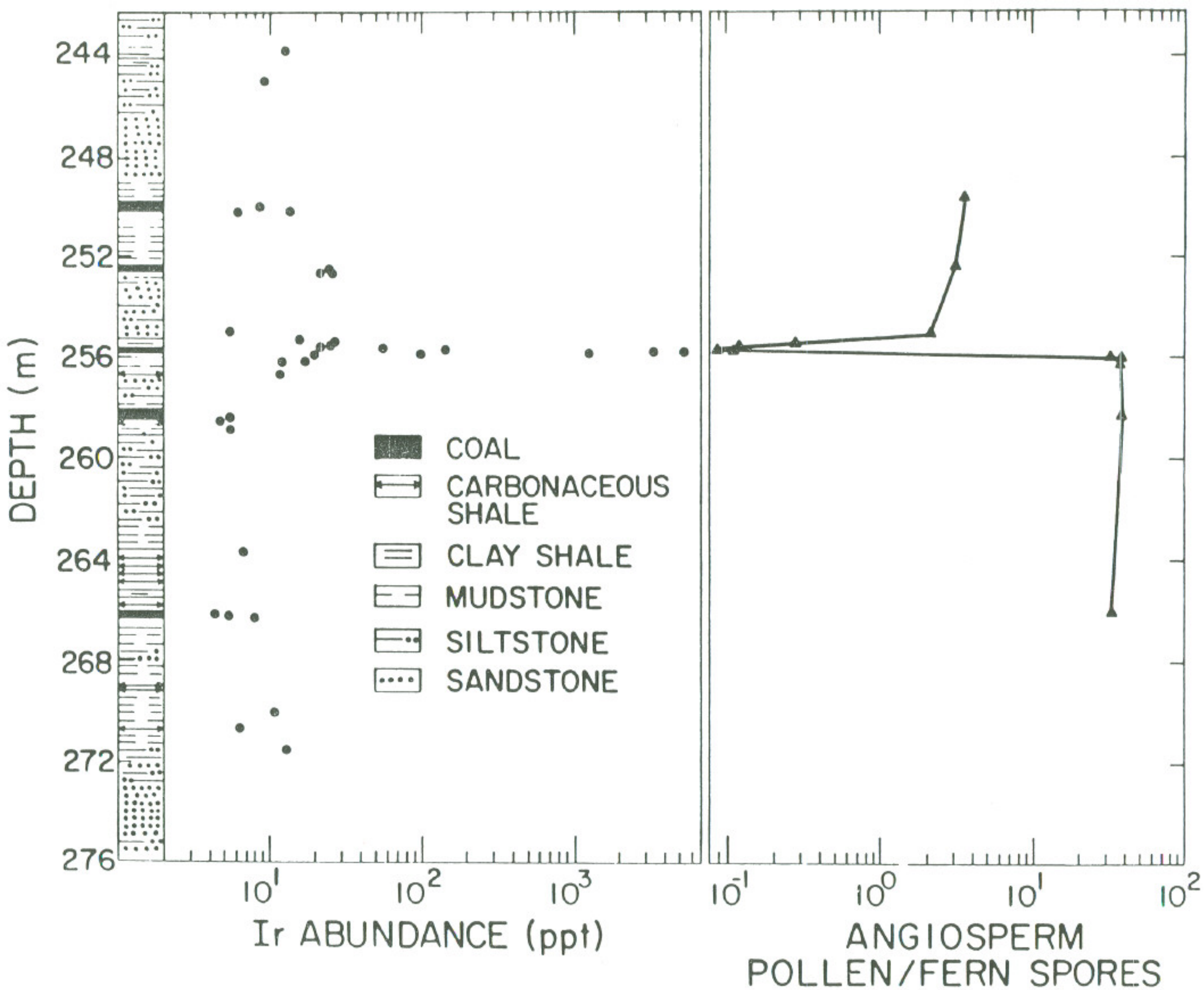

Fig. 9

XBL 819-1987

to be one of the most exciting diagrams I've ever seen. The vertical scales on the two halves are identical, but now we see the fossil pollen density increasing to the right, again on a log scale. It is clear from these data that the flowering plants really did feel the K-T extinctions, and that the paleobotanists we had talked to were simply wrong. Carl Orth and his colleagues published a magnified plot of both the iridium abundance and the pollen density, and the striking feature is that the extrema of the two peaks occur in the same centimeter of stratigraphic height, thereby eliminating pure coincidence as the cause of this otherwise surprising observation. I don't know the sedimentation rate in the Raton Basin, but if it is about the same as in the nearby Montana dinosaur territory, then on the average 1 centimeter corresponds to about 100 years. The first time I showed figure 9, I predicted that before long, it would be prominently displayed in all textbooks on geology and paleontology. It is too soon to check that prediction, so I'll return to my list of scientific predictions of the impact theory.

Figure 9 shows that the log of the pollen density recovers to about half its old value, shortly after the iridium layer was laid down, and that the recovery might have been complete, if one species of pollen-producing plants hadn't been permanently eliminated. People who study fossil pollen are called palynologists, and one of the best of them was the late Bob Tschudy of the U.S. Geological Survey. He was the key member of the Los Alamos team that found the "pollen break," and since then, he located it at continental sites in a number of other western U.S. states, by looking for the "eliminated species." If he saw it in a sample, he would move upward until it was gone, and if he started too high, it would be missing, so he would move downward. So his measurements gave him the direction to the K-T boundary. In that sense, his technique is like looking at the forams in Italy, and is far superior to the iridium method as a way of finding the K-T boundary.

In that method, you get no information if you are looking above or below the boundary layer. Every time Bob Tschudy found the "pollen break," he would send his rock samples to Carl Orth's lab, and there was always a coincident iridium peak.

The next four predictions involved several chemical properties of the K-T boundary clay. The easiest one to check was that the gross elemental composition of the Danish K-T boundary clay would be different from that of the clay that comprises 5% of the limestone above and below the layer. As far as I can tell, most of the geologists who were aware of the existence of the K-T boundary clay had naturally assumed that it came from the same source that supplied the clay component of the limestones—material eroded from the continents, and washed out to sea by rivers, to mix with the calcium carbonate from dead marine animals. When Walter first showed me a sample of the K-T boundary clay, between the latest Cretaceous and earliest Tertiary limestones, he indicated that the simplest explanation for the clay was that for some unknown reason, the calcium carbonate stopped accumulating on the ocean floor for several thousand years, and during that time, the clay continued to be washed down from the continents. That scenario would lead to the trivial prediction that the elemental composition of all three clays (K, T, and K-T boundary) would be the same. Our theory agreed that the gross chemical composition of the K and T clays should be identical, but predicted surprisingly, that it would be different from that of the boundary clay, because the latter came from a different place. I'll call that prediction number 7, even though it was the first one we were able to confirm. Figure 10 shows the chemical composition of the three clays from Denmark, for elements whose abundances vary over a wide range. These observations could have been made in much earlier times, since most of the measurements can be made using the traditional techniques of analytical chemistry, and don't require the availability of modern neutron

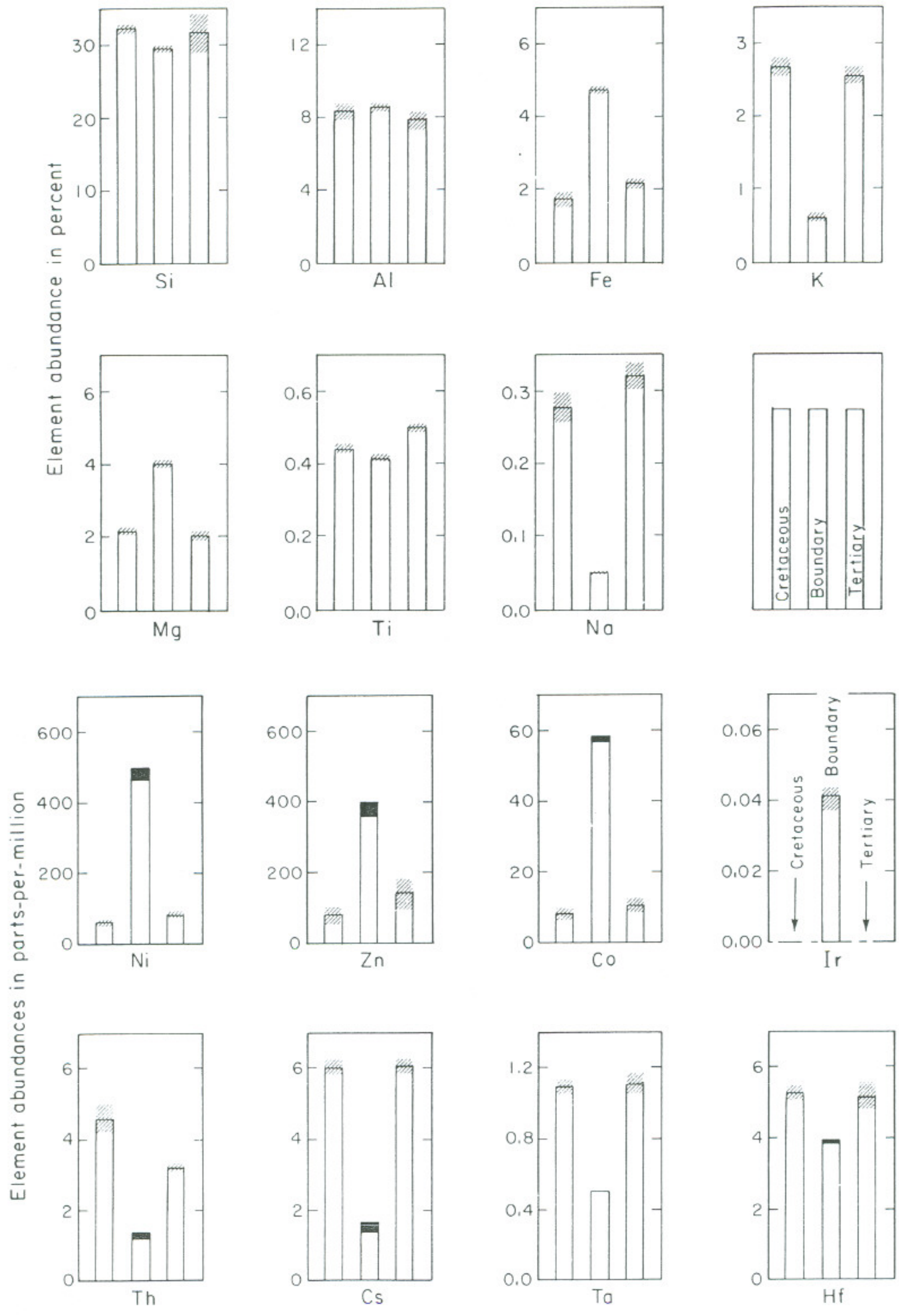
Element abundance in percent
Si
Al
Fe
K
Mg
Ti
Na
Cretaceous
Boundary
Tertiary
Element abundances in parts-per-million
Ni
Zn
Co
Ir
Th
Cs
Ta
Hf
XBL 8612-9290

Fig. 10

activation analysis.

Our next prediction in the chemical field was number 8, and it was that the "chemical fingerprint" of the boundary layer clay should have been the same, worldwide, when it was deposited. This means that the plot of elemental abundance in the boundary layer versus atomic number would be the same, at all locations, if no changes had taken place in the last 65 million years. It took longer to confirm this prediction, and partly because the present day trace element composition depends to some extent upon the oxidizing or reducing state of the ocean at the time the deposit was made. By working with regions of comparable ocean chemistry, Frank and Helen have shown that this eighth prediction is remarkably well confirmed. Figure 11 shows a comparison of chemical fingerprints between K-T boundary clay taken from sites on opposite sides of the globe—in Denmark and from a drill hole in the Central Pacific. Each point is for a certain element, and its position tells its fractional abundance at the two sites. So if the "fingerprints" were exactly the same, all the points would lie on the 45° line. Experts on the composition of ancient pottery, such as Frank and Helen, look at figure 11, and say, "These two clays came from the same quarry." They can say this because when they made a similar plot comparing boundary clay from two Danish sites, a kilometer apart, they found the same small average departure of points from the 45° line. And of course, the common quarry was the crater excavated by the bolide, 65 million years ago, and that confirms prediction number 8. And always, that fingerprint is quite different from that of the clay above and below the boundary. The boundary clay is, in geological terms, "exotic;" there is nothing like it in the solar system, so far as we know. It is, in fact, indistinguishable from one part chondritic meteorite plus ten parts earth's crust.

Some people say they might believe the theory, but they are troubled by the fact that

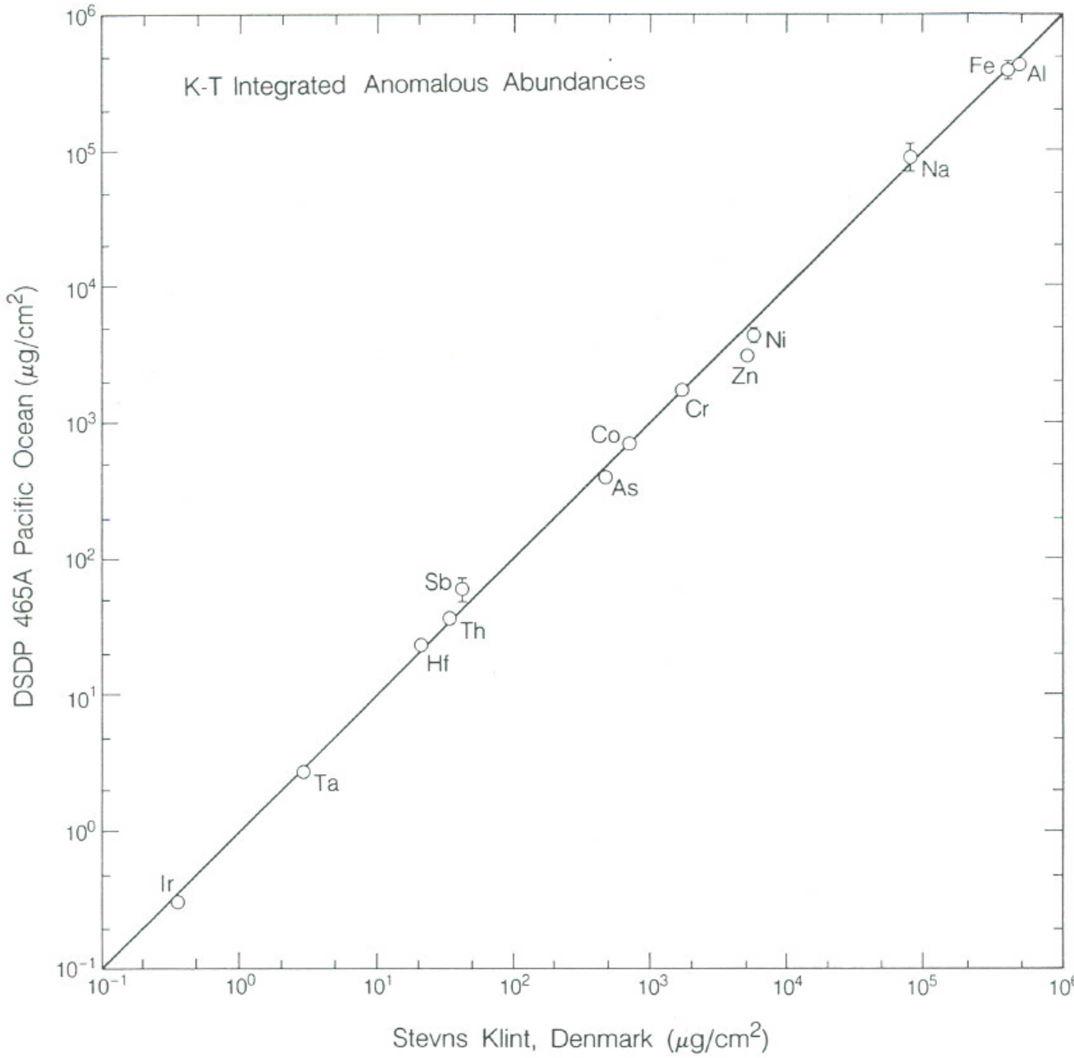

Fig. 11

XBL 846-8958A

the expected approximately 150 kilometer diameter crater hasn't been found. But if we compare the total ocean area with the total land area, it is clear that the betting odds favor the bolide landing in the ocean, where its crater would probably escape detection, and certainly so if it had subsequently been subducted. And in addition, large areas of the earth's surface have been erased by erosion, glaciation and mountain building, or covered by thick sedimentary deposits, so the bolide could have hit a land area, and still not be found.

In 1982, Karl Turekian,[11] published an article in GSA Special Paper 190, in which he proposed an ingenious test to be made on K-T boundary clay, and that (as he told us in Berkeley) he believed would show the boundary clay to be of terrestrial, rather than of extraterrestrial origin. Karl pointed out that because rhenium-187 is radioactive, and decays to osmium-187, with a very long half life, the osmium found at various sites would have isotopic ratios of 187 to 186 that depended on their past history. In particular, he noted that this isotopic ratio is now about unity for meteorites, but between 13 and 30 for crustal rocks. The measurements he later made, with J.M. Luck[11] showed that the osmium in the K-T clay layer was certainly not of crustal origin, but was consistent with being of bolide origin. That is what the theory predicted, so I will chalk it up as confirmed prediction number 9.

The fourth chemical test of the theory was really a postdiction, which both we and R. Ganapathy,[12] of the Baker Chemical Company recognized independently, at the same time. We could have articulated it earlier, but neither of our groups did so. But we, and more thoroughly he, found that the fingerprint of siderophiles in the K-T boundary clay was indistinguishable from that in the most common meteorites—the chondrites, and quite different from that in any known terrestrial rocks. Up to this point, I have concentrated on the measurement of iridium abundances, simply because iridium is the easiest of the siderophiles to measure by neutron activation, due to its exceedingly large capture cross section for slow neutrons. But the work I'm now describing suggests that had our analytical techniques been more sensitive, we could have done our work on any of the siderophiles—platinum, osmium, or even the lighter ruthenium, rhodium and palladium, and all our conclusions would have been the same, including the diameter of the bolide. That is the result of our belated test of the tenth "prediction" that follows directly from the bolide impact theory.

Now that I have introduced the concept of postdictions as useful tests of the theory, I will tell of three other postdictions, numbers 11, 12 and 13. The first two of this class are that there should be evidence, in the K-T layer, for both the high temperature generated by the impact, and the accompanying high shock pressure. The high temperature signature was first seen by the Dutch paleontologist, Jan Smit,[13] and it has been studied extensively by one of Walter's students, Alessandro Montanari. The signature is in the form of sand-sized spherules (Figure 12) made of a mineral usually formed at high temperature, and called sanidine. But in this case, it is a low temperature replacement of basaltic glass, the real indicator of the high temperature. Smit found the spherules first in a remarkable K-T boundary layer at Caravaca, Spain, that is only one millimeter thick, and that he found was highly enriched in iridium. Jan and Sandro have found the spherules in K-T boundary clay at sites all over the world, and have studied their mineralogy with a number of techniques, including x-ray diffraction. When I tell how we now know that the K-T boundary material was transported from the impact crater to sites all over the world, in ballistic orbits outside the atmospheres, rather than in the stratosphere as we had originally thought, I believe you will agree that that rules out volcanos as a source of the

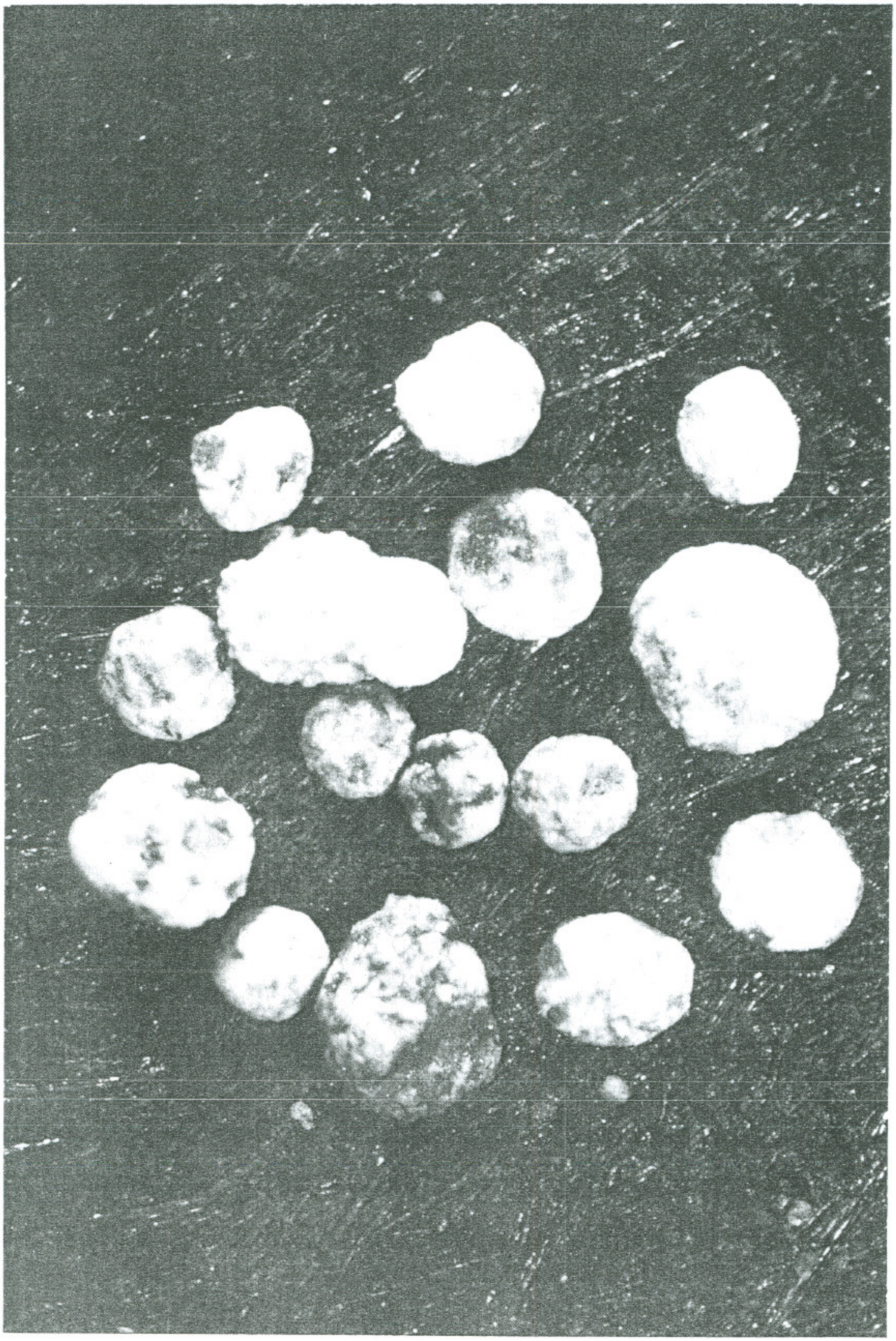

Fig. 12 CBB 835-4063

sanidine spherules. There is certainly no chance that wind could carry sand-sized particles to large distances in the atmosphere, to which volcanic ejecta are confined. But ballistic orbits outside the atmosphere are available to the ejecta from impact craters, as I will soon explain, so the worldwide appearance of sanidine spherules in the K-T boundary clay is to be expected from our theory, (prediction number 11) and contradicts the volcanic theories that have been proposed by some geologists to explain the extinctions and the increase in iridium concentration. (Volcanic layers are frequently encountered in limestone deposits, and they often signal their presence by a drop in the already low Ir content, rather than a rise. So I am puzzled that volcanos continue to be mentioned as possible sources of large iridium enhancements, such as we see at the K-T boundary.)

One straw at which volcano enthusiasts have grasped is the finding of enhanced iridium in aerosols from the Kilauea volcano.[14] That observation doesn't help explain either the sanidine spherules or the shocked quartz, and in spite of the efforts of some to use it to explain the iridium enhancement, the observers, themselves, come out strongly in opposition to such efforts. They say, "The Kilauea-type aerosols cannot account for the other" (than gold) "observed siderophile element abundances in the (K-T) boundary clay layer, which must be derived from the impacting projectile."

The second postdiction of this class was the discovery, by Bruce Bohor, of the U.S. Geological Survey, of shocked quartz in the K-T boundary layer in Montana, and later, in many other locations.[15] (Figure 13) Until its discovery in the boundary clay, this altered form of quartz had previously been seen in only two kinds of locations, both of which involve not only high pressure, but high shock pressure. The first was near known impact craters, such as the one in Arizona, and the second was near the sites of underground nuclear explosions, in Nevada. I have never seen a sample of shocked quartz, but I did

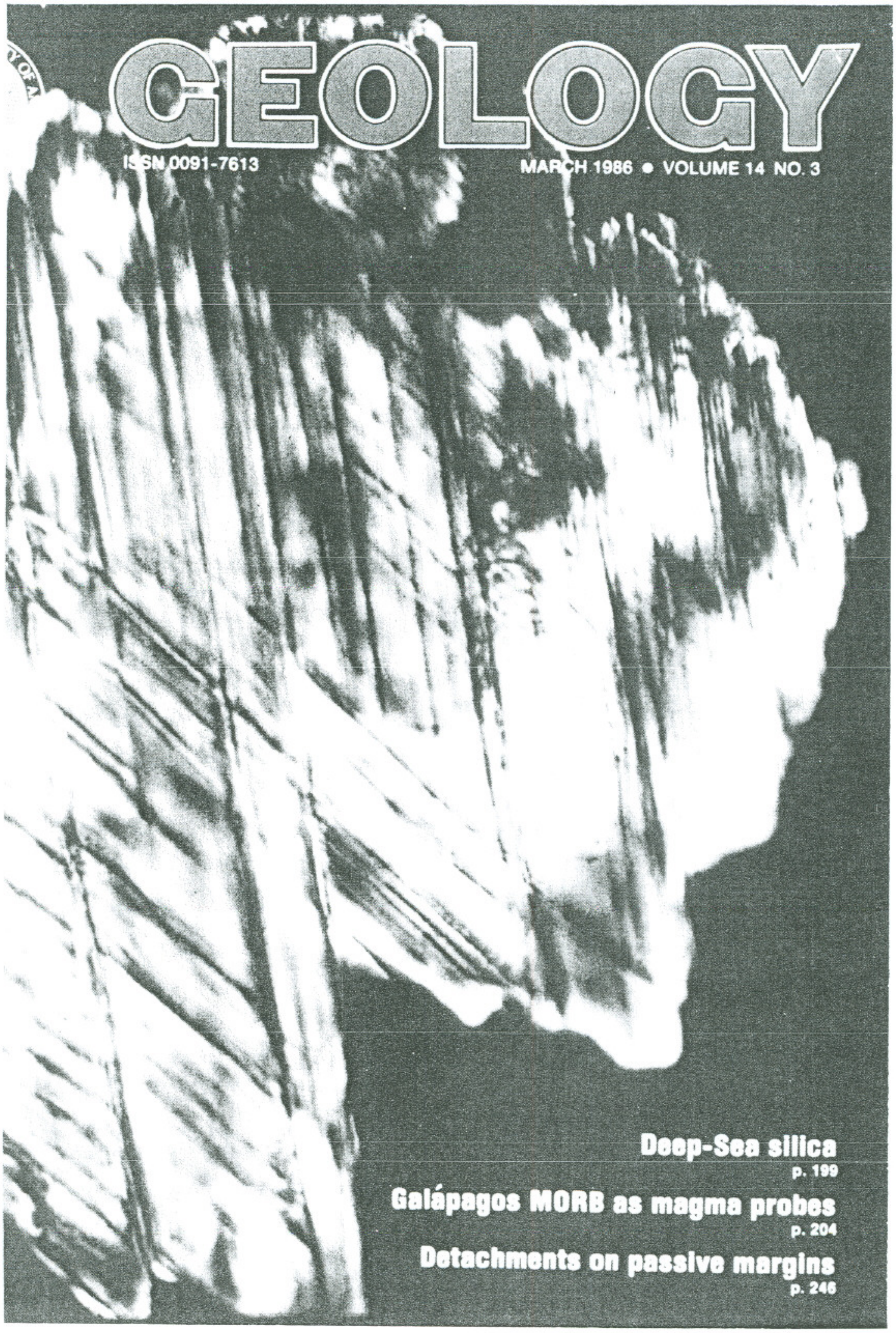

Fig. 13 CBB 871-112

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observe a sort of shock wave that passed through the earth sciences community when Bohor announced the discovery of shocked quartz. I had a long conversation with an old friend who had written an article that strongly criticized the bolide impact scenario, and asserted that the iridium layer came from volcanos. When I told him of the discovery of the shocked quartz, and asked what that did to his volcanic ideas, he immediately said, "There's no way volcanos could make shocked quartz, so you must be right about the bolide impact." Most of the geologists who had been "sitting on the fence" at this time accepted Bohor's discovery as the "smoking gun," and quickly embraced the bolide impact as the source of the K-T boundary clay. I think it is important to remember that shocked quartz is a known consequence of bolide impacts, and that it has never been seen in association with volcanic activity.

I'll now report on another postdiction—number 13 on the complete list. This is the discovery by the Chicago group of Edward Anders and his young colleagues, Wendy Wolbach and Roy Lewis,[16] that the K-T boundary clay includes an amount of soot that could only result from the burning of an appreciable fraction of all the biomass present on the earth, 65 million years ago. Of course their discovery is dependent on our experimental demonstration that the K-T boundary clay was deposited in about a year, and not in the several thousand years one would calculate from its stratigraphic thickness divided by the normal K or T sedimentation rate. I believe the Chicago results show that the soot came from burning forests, but as frequently happens in the development of a new theory and it did happen with ours, the basic idea may be sound, but some details may have to be changed, and in the process, the theory is strengthened. In a recent exchange of letters about soot, Edward Argyle[17] criticized the Chicago scenario, which had the forest fires being set by infra-red radiation from the fireball over the impact crater. He said the fireball wouldn't be high enough to set fires over a large enough area on land, and secondly, that such fires in green forests, generally burn out in a few days. But since he was impressed by the evidence for widespread fires, he came up with an alternative scenario to explain them. He adopted the well supported view that the dust cloud dropped the temperature to the point that there was "extensive killing (but not necessarily extermination) of the tropical rain forests." He suggested that in months, the forests would be in a desiccated and flammable state, and therefore highly susceptible to ignition by lightning strikes, which would, of course, have occurred worldwide. Anders accepted Argyle's suggestion. I think it reinforced Anders' conclusions, and provided a more plausible explanation for the fires which his soot evidence indicated had really taken place.

Now that we have seen how Anders' theory was strengthened when someone pointed out a problem, and then found a way to circumvent that problem, I'll tell of a time when a similar thing happened to us. In my experience, good theories are strengthened in this way, and poor theories frequently collapse when someone points out a serious flaw in the argument. Our original paper suggested that the suspended dust in the atmosphere, and the resulting darkness, would last for about three years. This estimate was scaled from the well documented explosion of Krakatoa, in Indonesia, a century ago. But Turco, Toon and their Ames Research Center colleagues,[2] after showing that the temperatures would go down to about zero, Fahrenheit for several months, found that the famous 19th century physicist, Sir George Stokes, had made two compensating errors at that time, that would forbid us from extrapolating from a volcanic explosion to an impact explosion. The problem was that "our dust" would remain aloft for only a few months, and it would fall out before it could be transported in the atmosphere between the northern and southern hemispheres. Since we had seen the iridium in both hemispheres, something was seriously wrong with our notion that the inter-hemispherical transport had taken place in the atmosphere. It was obvious that there was enough incoming energy to get all of the bolide mass plus the observed ten times as much weight of crustal dust into ballistic orbits, outside the atmosphere, but I had felt sure that atmospheric drag would rule out that possibility. Fortunately, two independent teams of computer experts, John D. O'Keefe and Tom Ahrens,[18] of Cal Tech, and Eric Jones and John Kodis,[19] of Los Alamos used their hydrodynamics computer codes to show that after the bolide impact, the rising fireball would accelerate the dust from the bolide plus the extra crustal dust upward through the atmosphere into ballistic orbits, to spread it worldwide in about an hour.

The paleontologists who knew most about marine flora and fauna had earlier said that our postulated three years of darkness would wipe out far too many of the marine species, but they expressed support for the revised "few months" of darkness, as being consistent with the damage the fossil record showed. So after our little excursion into and out of trouble, we ended up with a stronger theory.

Now that I have shown that our original time scale presented too severe an environmental crisis for some species to tolerate, I'll address briefly a topic that greatly troubles some paleontologists. They see very little in the way of a pattern to explain why some species survived the crisis, while other related ones were wiped out. I have no problem with that, based on my extensive experience with the effects of increasing doses of nuclear radiation on animals. Figure 14 shows how the surviving fraction of an original population of animals varies with increasing radiation dose. Similar curves are known for what biologists call other "insults" to the population, such as doses of chemical poisons, heat, lack of oxygen, etc. They all start at 100%, at low doses, and stay there as the intensity of the insult is increased. But then the curve falls off, as the insult does its increasing damage,

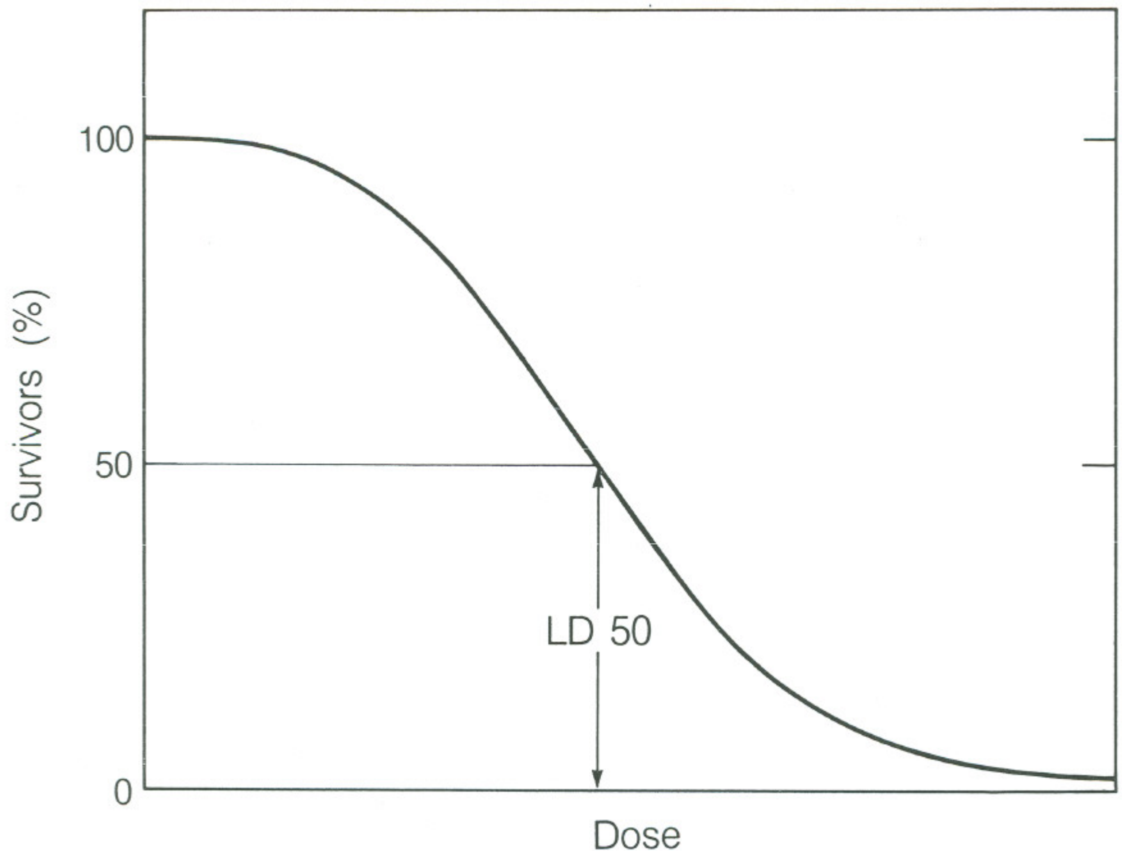


Fig. 14

XBL 8612-9289

and finally, it gradually approaches zero survivors. All such curves that I know of have this general shape, and the amount of insult to give a 50% survival is called the LD50, for lethal dose, 50%. Most of the work in radiation biology has been concentrated on the lower doses, and on the small and difficult to measure cancer-producing or fatality rates at such low doses. For the purpose of understanding mass extinctions, it is important to concentrate on the right hand section of the curve, where it approaches zero survivors. If the insult is large enough to predict a survival of 10^{-6}, then if there were 10^{6} individuals in the original population, then that species would almost certainly be wiped out. But another species, with perhaps one hundred million individuals would have a good chance to escape extinction. And of course the details of the curve will vary from species to species, so that feature, plus the numerical size of the population can be the deciding factors in species survival or extinction. (We have all heard that if the operating insult is nuclear radiation, then the earth may be inherited by cockroaches, that have a greater tolerance for radiation than mammals.) To me, the most important thing to remember in this discussion is that we can divide environmental insults of the kind caused by a bolide impact into three classes, small, medium and large. If the insult had been small, no species would have gone extinct, the mammals would still be subordinate to the dinosaurs, and I wouldn't be giving this talk. If it had been large, all life on this planet would have ceased, so again I wouldn't be giving this talk. That tells me that the insult must have been of medium strength, and for the rather uninteresting reasons I've just mentioned, some species survived and others didn't. I think the smallness of the dinosaur population may have been an important contribution to its complete and sudden disappearance. Dale Russell, a Canadian expert on dinosaurs, reports[20] that the K-T extinction wiped out virtually all land animal species weighing more than 25 kilograms. Because population magnitudes are inversely related to individual weights, it may be true that the survival of the lighter weight species depends more on their larger population than on their smaller body weights. I doubt that we will ever know the details of why certain species survived, and others went extinct, and it may even be a mistake to try to identify the difference between the two kinds. To me, that could be like trying to find out in what significant way two neighbors in California differ, that explains why one of them won 4 million dollars in the state lottery, while the other got nothing.

I've mentioned dinosaurs a few times in passing, but I'll now address that question directly. You will remember that when Walter first showed me the K-T clay, he mentioned the near coincidence of its deposit with the extinction of the dinosaurs. I will now show that the bolide impact was responsible for the extinction of the dinosaurs. If Walter and I had known then what we know now about these wonderful animals, here is what we would have said, in the form of prediction number 14: "If the bolide impact was responsible for the extinction of the dinosaurs, as it obviously was for the forams, then we should find the iridium-rich clay layer just above the 'highest dinosaur fossil.' We see the forams with nearly constant surface density on our rock faces, up to the iridium layer, where they suddenly disappear. So we will believe the bolide, which we know can cause some extinctions, caused the extinction of the dinosaurs if we find dinosaur fossils with nearly constant surface density up to the 'highest dinosaur,' with none higher." (Dale Russell, has published a graph showing that they behaved that way.)[21] We obviously can't expect the iridium layer to be a fraction of a millimeter above the highest dinosaur, as it is above the highest forams. So by what measure do we judge that it is "just above" the highest dinosaur, as our prediction says it should be, and as it is "just above" the highest forams? It is easy to show mathematically, that if the dinosaurs had been flourishing before a sudden extinctions, as they had been flourishing for the previous 140 million years, and if the iridium layer really marks the time at which they underwent a sudden extinction, then the following will be true: the most probable position of the highest dinosaur fossil will be below the Ir layer by a distance exactly equal to the mean vertical spacing of such fossils. The probability that the highest fossil will be found twice as far below the layer is $e^{-2} = 0.14$. And we can use that mean spacing as a reasonable mean error on that predicted position.

So with that as a prediction, we ask our paleontologist colleague, Bill Clemens, to collect rock samples above the highest dinosaur in his research area, in Montana, so we can test them for iridium. He tells us that the highest 17 articulated fossils in his section had an average vertical spacing of almost exactly one meter, and despite what many dinosaur experts have said, there is no indication in his data of a gradual decrease in fossil surface density with height. (Articulated fossils are ones in which two or more bones are in their expected relationship, and are nearly the only ones considered seriously by careful paleontologists; very large single bones are also acceptable. The bone fragments that are frequently found above the iridium layer are of no interest, since they could have been moved by running water, or by animals that lived much later.) On a larger linear scale, we find that the articulated fossils behave just as the forams did, with a sudden cut off at the iridium layer. So we predict that the iridium layer (not yet seen) will be close to 1 ± 1 meter above the highest observed fossil. After Frank and Helen found the iridium layer 2 meters above Bill's highest fossil, we felt that our prediction had been well confirmed. (We have seen that iridium layers are exceedingly rare in the fossil record.) But Bill still faults the impact theory because the iridium layer wasn't at the level of the highest fossil, and continues to talk about the existence of the "2 meter gap" as having disproved the impact theory. We know the most probable gap would be 1 meter, but Bill's desired gap of zero meters, and the observed gap of 2 meters are both consistent with the predicted value of 1 ± 1 meters. So we consider prediction 14 to be satisfied, and we don't doubt that the unique bolide impact (figure 9) was responsible for the unique event that was discovered more than a century ago, by paleontologists—the sudden, and until recently, mysterious extinction of the dinosaurs.

We continue to hear that paleontologists have recently disproved the more than a century-old scenario of the sudden extinction of the dinosaurs on land, in the sea, and in the air (after 140 million years of adaptations to serious temperature and sea level changes in their environment.) The latest such story was published in the New York Times,[22] just a month ago, and says that dinosaur fossils were found 500 feet above the K-T horizon, corresponding to a million years into the Tertiary period. But then we are told that the investigator (Robert E. Sloan) "said the identity of most of the post-Cretaceous dinosaurs could not be determined because the bones were too fragmentary". (Emphasis added.) That indicates to me that non-articulated fossils were used to arrive at an invalid conclusion. Walter says he finds it strange to hear that our theory is wrong because paleontologists have shown that the dinosaur extinction did not occur at the time the iridium was deposited—Clemens has shown that the dinosaurs died out before the iridium event, and Sloan has shown that they lived for a million years afterwards! I continue to accept the conventional paleontological wisdom that the dinosaurs finally did meet an environmental crisis that they couldn't tolerate, and I've given my reasons for believing that that crisis was initiated by the "expected" ten kilometer diameter bolide.

Occam's Razor tells us that when we find two extraordinary events that can be tied together, as cause and effect, by a "reasonable" theory, we shouldn't take seriously other theories, particularly when there is no valid evidence to support such theories.

At the present time, those who don't accept the impact theory of extinctions appear to have only two suggested alternatives. One is a volcanic eruption, which I've mentioned several times as being in strong disagreement with three observations—the worldwide distribution of sanidine spherules, the greatly enhanced iridium concentration in the K-T boundary layer, and the widely observed presence of shocked quartz in the layer. So I see no way in which the volcanic origin of the K-T layer and the extinctions can be taken seriously. Before a theory can begin to make predictions, it must first agree with all the known observations, and volcanic theories are in serious discord with such known observations. But we can't dismiss the idea that volcanic eruptions were triggered by the bolide impact, so the K-T extinction could easily have associated volcanic eruptions.

An alternative theory that appeals to many paleontologists is that the dinosaurs went extinct as the result of wide excursions of temperature, or sudden changes in sea level. We can rule out sea level changes as being of any consequence, by noting that in the 140 million years during which the dinosaurs existed, the sea level had dropped suddenly by about 150 meters on two occasions,[23] the same amount it dropped suddenly at the K-T horizon, and the dinosaurs didn't react adversely to those earlier changes. But one should expect sudden drops in sea level to <u>follow</u> bolide impacts, as Don Morris and Rich Muller have shown,[24] in their theory to explain the magnetic reversals that frequently coincide with extinctions. The sudden drop in temperature can deposit ice on the continents, thereby lowering the sea level.

Returning to the dinosaurs, we see no evidence that the many sharp drops in sea level were threats to the existence of the land-based dinosaurs—and even if they were, why would they cause the nearly (or exactly) simultaneous extinctions of marine dinosaurs or of the flying pterosaurs? (One can even ask the question, "How could a marine reptile tell that the sea level had gone down by one hundred meters, and if it could notice the change, why would that change affect its ability to live?") We have a good geological record of ocean temperatures, from the measured oxygen isotope ratios, and again the dinosaurs had weathered many such sudden changes in temperature,[25] with no apparent trouble. We have seen that a sudden temperature change should be expected as a result of a bolide impact, and Ken Hsű et al.[25] have observed it at the K-T horizon. Toward the end of their paper, they say, "Our data suggest to us that the catastrophic environmental changes at the beginning of the Tertiary were the consequences of mass mortality in the oceans, not the causes." And as a final argument against sea level changes, and temperature excursions as the cause of the extinction of the dinosaurs, there is no way to associate the iridium layer (which must be explained) with such environmental changes, except through a bolide impact, which would certainly cause such changes. (And we should remember that there is good evidence that the earth has been hit by 10 kilometer diameter bolides, many times during its 4.5 billion year history.)

I think it is now time for those who felt comfortable in ignoring the impact theory, seven years ago, to recognize that it is the only existing theory that agrees with all the known observations. So I feel the shoe is now on the other foot, and those who are pushing for the acceptance of non-bolide theories of the K-T extinction should now tell how they can overcome the many objections I've outlined in this talk, to keep their theories alive. If they can't do that, and I don't see much chance that they can, they have only two choices: they can either accept some form of bolide impact theory, or come up with a new, non-bolide theory that agrees with all the known observations. I think the chances of finding such a theory are rather remote, but I can't rule them out. But before any scientists embark on such a search, they should remember that bolide impacts in the 10 km diameter class are part of uniformitarianism, in the same sense that magnetic reversals are, (infrequent, but certainly not unexpected) so if the K-T extinction was not caused by a bolide impact, where is the evidence for such an expected impact, with its now well understood signature?

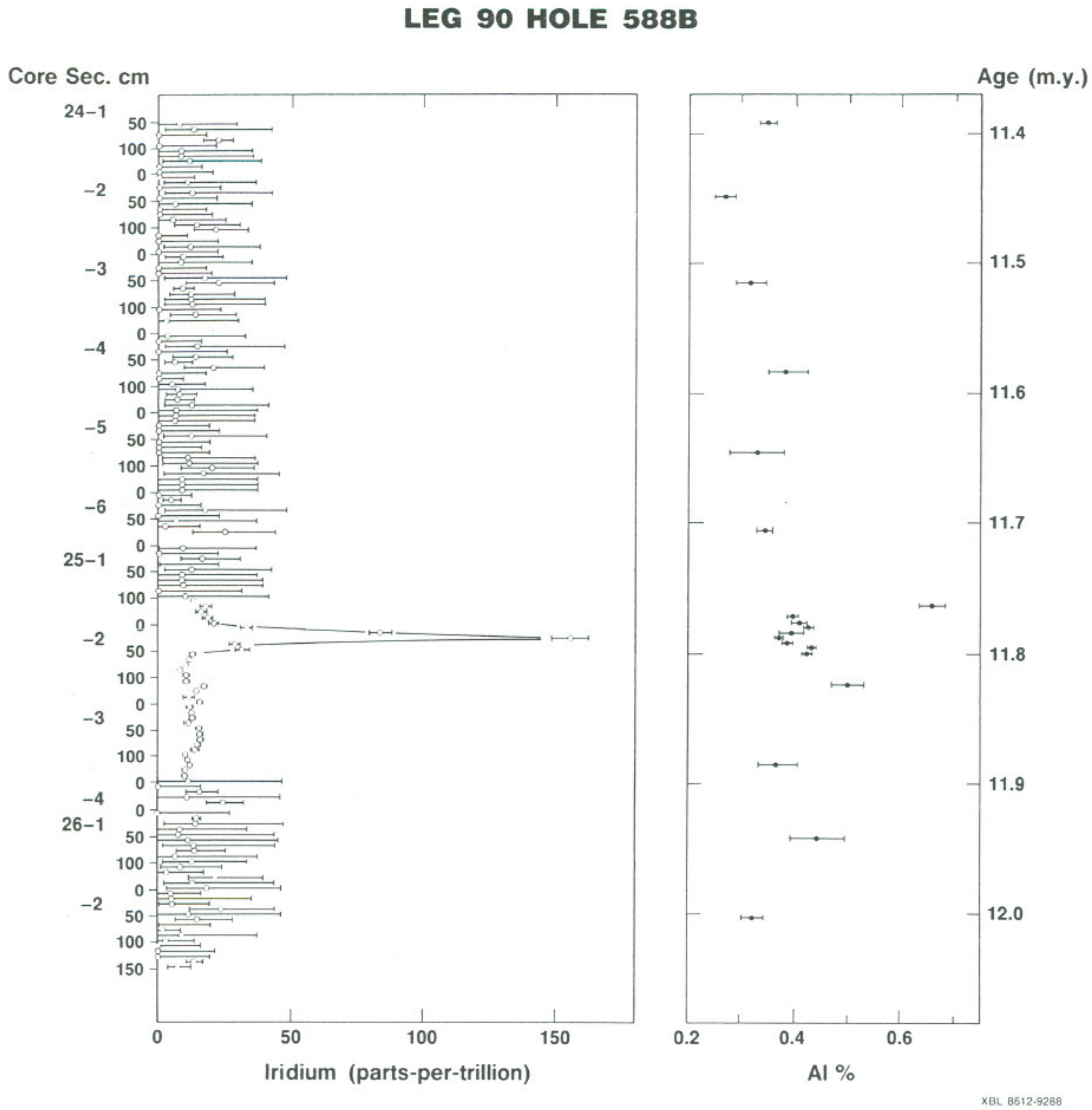
Almost all of the genera that have ever existed on the earth have undergone extinction. So the five major extinctions shown in figure 6 stand out above a huge background of ordinary extinctions. Until recently, it was thought that mass extinctions and background extinctions differed only in their "intensity," as measured, for example, by the number of families lost per million years. I believe our work led people to reexamine that postulate, and it has now been found, by Dave Jablonski, to be incorrect.[26] He points out that genera can protect themselves from ordinary extinctions, in two ways (1) by diversifying, meaning evolving larger numbers of different species—they all have to be killed before the genus can be said to be extinct—and (2) by spreading themselves over wide geographical areas. But Jablonski finds that those protective measures don't help a genus escape a mass extinction. I think it is correct to say that a background extinction takes place when a genus loses the Darwinian battle for the survival of the fittest—one species against another. But in the K-T mass extinction which Jablonski studied, there was no way that a genus could have evolved to protect itself from an occurrence that happens suddenly once every one hundred million years or so. So the fittest still do survive, but Darwin's slow-acting natural selection can have played no part in making the survivors more fit. And I think we can add that as a postdiction of our theory, to bring the total up to 15 separate tests, all passed with high marks.

Some of you may have read the talk I gave in Washington several years ago, in which I said that all but one of our predictions had been fulfilled and fortunately that partial failure had no negative effect on our theory that the K-T extinction was caused by a bolide impact. We couldn't help noticing that there were five major extinctions in the last 500 million years (Figure 5), and that a bolide of the kind that caused the K-T extinction should hit the earth on the average of once every 100 million years (Figure 4). We wouldn't have been responsible scientists if we hadn't suggested that all of the five "majors" could have had similar origins, in which case, we should find iridium layers associated with all five. So we and other groups have looked for iridium enhancements at the four other major extinctions, with not as much success as we had hoped, but we certainly didn't "strike out." The most severe mass extinction was about 250 million years ago, at the Permian-Triassic boundary. We analyzed clay from a Chinese P-T layer, and showed that its iridium content went sharply downward—one of the signatures of a volcanic deposit. A Chinese group reported a large iridium enhancement in that same layer, in the same quarry. It has been our experience that when two groups analyze the same sample, the one that finds the smaller amount of iridium is usually right; it is easy to contaminate a sample, but quite impossible to accidentally "decontaminate" one. Of course, we hoped that the Chinese measurements were correct, but they were later revised downward, to be in substantial agreement with ours. There are reasons to believe that both of our groups looked below the real P-T boundary, so we plan to look higher up. We will join forces with our Chinese friends next year, and will collect P-T samples over a much wider span of time.

Carl Orth and his group[27] have found an iridium enhancement near the Late Devonian mass extinction, another "major", but he cites evidence to show that it came from the ocean, through a biological concentration process. So at the moment, the K-T extinction appears to be the only one among the majors that was certainly caused by the impact of an iridium-rich bolide.

For mass extinctions of the second rank, there are at least two that have associated iridium enhancements. We and Ganapathy independently found the one at the Eocene-Oligocene boundary, about 38 million years ago. We have since shown that it consists of two or perhaps three closely spaced iridium "spikes." And very recently, using our new detector, we have found a sharp iridium spike (Figure 15), laid down eleven million years ago. This figure shows a set of points with larger error bars, where the detector was used in the "search mode." Then, after the 150 parts per trillion spike showed up, we remeasured all the neighboring points for longer times, and thereby reduced their statistical errors. We plan to make a continuous search of the last 250 million years of the geological record in this way, over the next few years.

Three years ago, Dave Raup and Jack Sepkoski[28] showed evidence that mass extinctions occurred periodically, with a time interval of 26 million years. (The three known Ir enhancements are all consistent with the Raup and Sepkoski timetable—11, 38 and 65 million years ago.) Figure 16 is a replot of their data, by my colleague, Richard Muller. The arrows are spaced 26 million years apart. You may have heard that Rich and his colleagues have suggested that the regularity shown in figure 16 derives from a postulated solar companion star, called Nemesis, with a period of 26 million years.[29] According to their theory, it perturbs the Oort Cloud near perihelion, and sends a shower of a billion comets into the inner Solar System, where several hit the earth by chance, in a time interval of a few million years. (The observed "fine structure" of the E-O iridium enhancement is best explained by a comet shower, but that shower could have come from a single "passing star," with no requirement for periodicity.) I am sorry that I don't have time to tell you more about this interesting and still developing story.


LEG 90 HOLE 588B
Core Sec. cm
Age (m.y.)
24-1
-2
-3
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-5
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50
100
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150
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0
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100
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Iridium (parts-per-trillion)
0.2
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Al %
XBL 8612-9288

Fig. 15

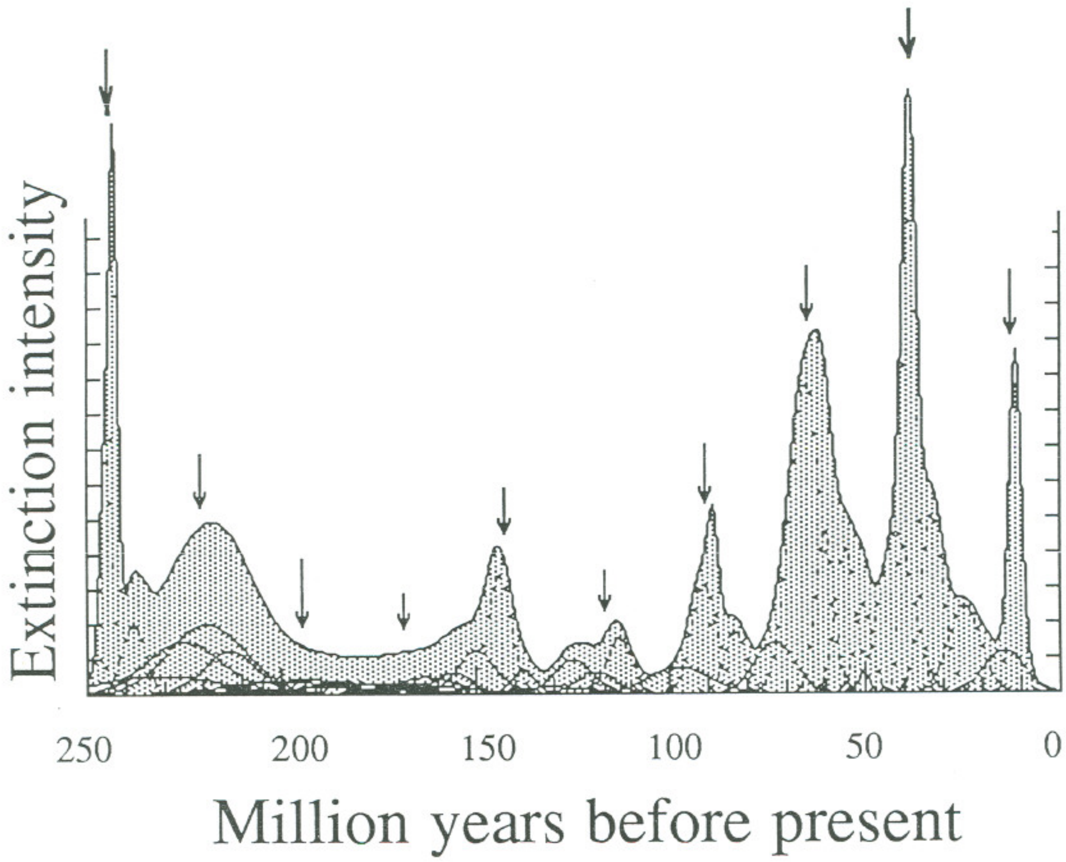

Fig. 16

XBL 8611-4774

I don't want to leave you with the impression that we know everything about impacts and extinctions. A question that is under strenuous debate at the moment has to do with reconciling the paleontologists' belief in long term extinction events, (more than one million years) and our demonstration that at least one at the K-T horizon is basically instantaneous. A fascinating paper that addresses this question has just been accepted for publication by NATURE, that has as its co-authors, astronomer Piet Hut, Walter and another geologist, plus four paleontologists and another astronomer. (That is certainly a "first.")

This paper's thesis is that many extinctions were initiated by comet showers, so each one really consists of several sharp extinctions of the kind I've discussed here, but spread out over the few million years it takes for the comet shower to be "cleaned out." This model has been advanced for several years by Rich Muller, and Erle Kauffman has given it the name "stepwise mass extinctions."[30] It has much in its favor—not the least of which would be the end to the debate over whether mass extinctions were geologically instantaneous, as I've described today, or spread out over a few million years, as most paleontologists believe. If Rich and the authors of this new paper are right, then the two views are equally valid; it just depends on how you look at the record. (Physicists debated for years about the nature of light, and went through periods when waves or particles seemed to be favored. But everyone is now happy with the idea of duality; you see either particles or waves, depending on how you look.)

So far, we have seen multiple iridium spikes at only one extinction event, the E-O, but there is other evidence for comet showers at several other extinctions. Walter and Rich Muller, as well as Rampino and Stothers showed that large terrestrial craters have nearly the same period and phase as Raup and Sepkoski's 26 million year extinction cycle.[31] That could only be true if some bolides were bunched together, as in comet showers.

No one has ever analyzed a comet or an asteroid for its trace element composition, so our knowledge of such objects comes from the analysis of meteorites, the only bolides that survive impact with the earth. As a first approximation, we have assumed that all bolides have the same composition, since they have the same origin, in the original solar nebula. But that is certainly an oversimplification; we know that all the planets have the same origin, but the four solid inner planets bear little resemblance to the gaseous Jovian planets. So we should expect that comets could be quite unlike the asteroids and meteorites; comets are probably mostly ice. (I've learned a great deal about comets from the recent semi-popular book, Comet, by Carl Sagan and Ann Druyan;[32] they say, "So it looks very much as though comets really are giant ice balls racing around the sun.") I know of no evidence to contradict the following hypothesis, which I haven't seen advanced in quite this way until now: (but see Ref. 14b) All the major mass extinctions, and all of the secondary ones (addressed by Raup and Sepkoski) were triggered by bolide impact, with most of the bolides being very icy comets, probably in retrograde orbits, to maximize the environmental insult, per unit of incoming iridium.[14] (This hypothesis has the advantage of explaining another otherwise very puzzling observation. Strewn fields of micro-tektites, generally believed to be of bolide origin, differ in one interesting way: some are rich in iridium, and others have no detectable iridium.) So, to use words I've used earlier, this is a reasonable hypothesis, that if true, would explain two otherwise puzzling observations, concerning extinctions and micro-tektites. And most importantly, it is testable—by those skilled in the art of finding shocked quartz. If they find shocked quartz at most of the extinction horizons, then I believe the cause of those extinctions will be established beyond all question, and we can all stop talking about the impact theory; it will then be established as a fact, just as the origin of the K-T extinction has been.

I have emphasized the observations that have convinced me, as a physicist, that the K-T extinction was caused by a bolide impact. I'll now try to look at the question from the geological point of view, by reproducing the final table (Figure 17) from a recent paper written by Walter,[1] entitled, "Toward a Theory of Impact Crises." You will see that volcanic eruptions of two different types are rejected as possible causes, but impact events are acceptable.

Now that I've told of some problems that remain in our understanding of the other extinctions, I'll return to the more thoroughly studied K-T extinction, and say that for all the reasons I've explored in this talk, I see no way to escape the conclusion that the K-T extinction, including that of the dinosaurs, was triggered by a 10 kilometer diameter bolide impact. And at least from our human point of view, that was arguably one of the most important single events in the 4.5 billion year history of our planet. Had it not taken place, the largest mammals alive today might still resemble the rat-like creatures that were scurrying around, 65 million years ago, trying to avoid being devoured by dinosaurs.

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Observational evidence	Impact event	Volcanic Eruptions quiet basaltic	violent siliceous
Iridium	**YES** all types of meteorites have high Ir	**POSSIBLY** high Ir in Kilauea gas; no other case known of high Ir	**NO** high Ir not found in any silicic ejecta
Spherules	**YES** droplets of impact melt, equivalent to microtektites	**YES** drops of liquid basalt; e.g. at Kilauea	**NO** violent eruptions produce angular fragments, not droplets
Shocked quartz	**YES:** shocked quartz is common at known impact sites	**NO** Large explosions do not occur in this setting	**Apparently NO** insufficient shock in volcanic explosions
Soot	**YES** fires set over vast areas by fireball	**NO** fires only very local	**NO** fires only very local
Worldwide distribution	**YES** predicted by computer models	**NO** no mechanism ever suggested	**NO** cannot penetrate atmosphere
SUMMARY	**ACCEPTABLE** accounts for all observational evidence	**REJECTED** on firm basis of shocked quartz and dis-tribution	**REJECTED** on firm basis of iridium and spherules

Fig. 17

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