Title

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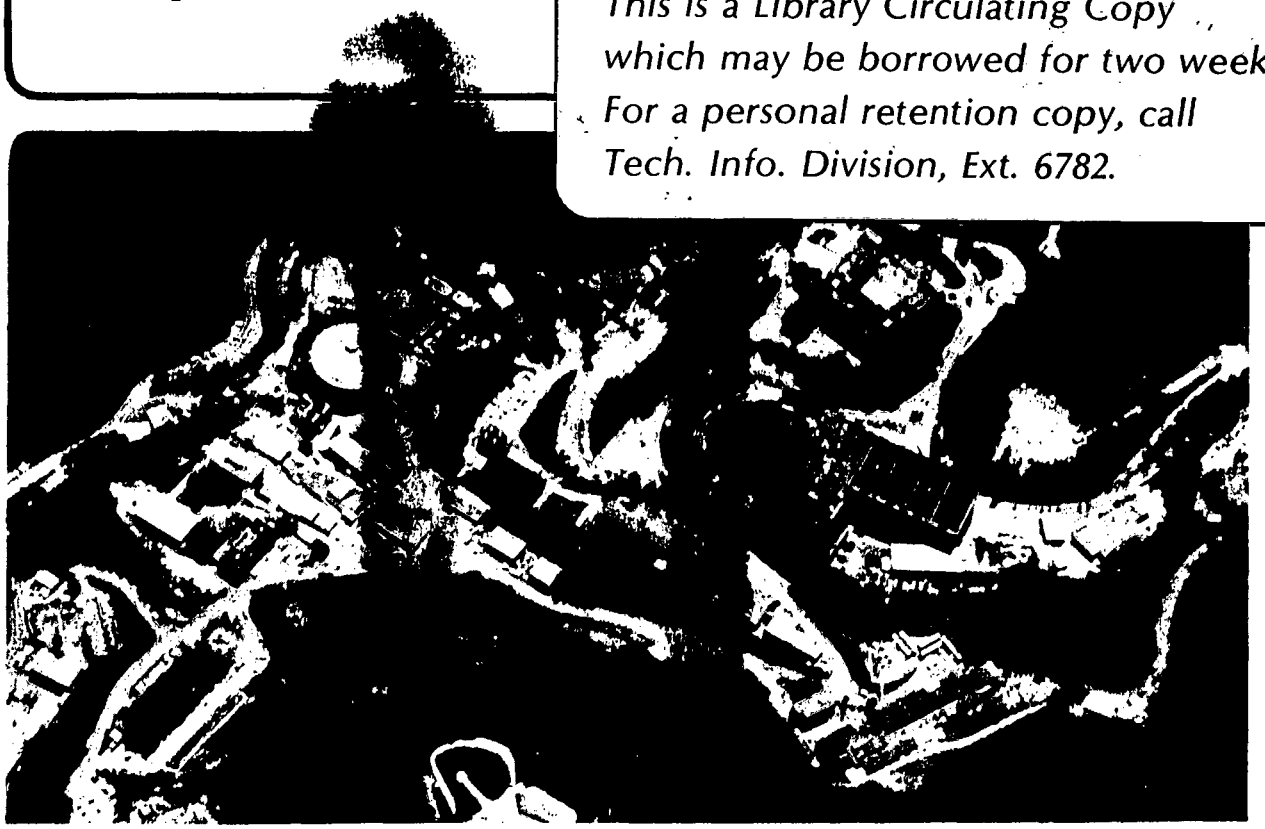

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I used to be able to say just about everything I know about this subject in an hour. I could develop it in historical order in a standard length lecture, but things have moved so rapidly in the last two years, that it is quite impossible to follow that scheme anymore. Therefore I am going to have to concentrate on the present state of our theory that an asteroid hit the earth 65 million years ago and wiped out large numbers of species, both on the land and in the ocean.

I think the first two points, 1) that the asteroid hit, and 2), that the impact triggered the extinction of much of the life in the sea, are no longer debatable points. Nearly everybody now believes in them. But there are always some dissenters. I understand there is even one famous American geologist who doesn't yet believe in plate tectonics and continental drift. We now have a very high percentage of people in the relevant fields who accept these two points. Of course, science isn't decided by a vote, but it has been interesting to watch the consensus develop.

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*An invited talk at the annual meeting of the National Academy of Sciences, April 18, 1982. To be published in the Proceedings of the National Academy of Sciences.

The third point, as to whether the impact of the asteroid had anything to do with the extinction of the dinosaurs and of the land flora is still very much open to debate, although I believe the answer is very definitely yes. But I will tell you about some of our friendly critics who think not. I will concentrate on a series of events which has led to a great strengthening of the theory. In physics, theories are declared to be strong theories if they explain a lot of previously unexplained observations, and even more importantly, if they make lots of predictions that are verified, and if they meet all the tough scientific challenges that are advanced to disprove them. In that process, they emerge stronger than before.

So, I am going to tell you of a number of predictions that our theory has made; almost without exception they have been verified, and I will tell you of several serious questions and doubts that have been raised concerning the validity of the theory. People have phoned in with facts and figures to throw the theory into disarray, and written articles with the same intent, but in every case, the theory has withstood these challenges. I will therefore concentrate on those things that show the theory to be a strong one, but I won't neglect a few "loose ends."

Instead of using the historical approach which has been my custom up till now, I am going to start by following the cub reporter's checklist that he learns in journalism school. Every story should contain who, what, when, where and why.

First of all, who? The original "who" were the Berkeley group. This is the title page of our first major publication,[1] which is an 86 page November 1979 Lawrence Berkeley Lab preprint [Fig. 1]. First, let me introduce my colleagues; we are in alphabetical order here. The second one is my son, Walter, who is a professor of Geology at Berkeley. Frank Asaro and Helen Michel are nuclear chemists at the Lawrence Berkeley Laboratory. All of us have been involved in every aspect of the problem, since the earliest days. I have even been out looking at some rocks in Italy--a new experience for me. Helen Michel has collected rock samples in Montana, where there are dinosaur fossils. Her husband tripped over a previously undiscovered Triceratops (horned dinosur) skull on one occasion. So, we haven't been a group of people each working in his own little compartment, but rather we have all thought deeply about all phases of the subject.

When we sent this paper to Phil Ableson, the editor of Science, he had two comments. In the first place, it was too long. He could not publish it unless we cut it in half. If you have read the paper,[2] you know it still turned out to be pretty long.

Secondly, Phil said, "I have published quite a few papers on the cause of Cretaceous-Tertiary extinction in the last few years, so at least n minus one of them have to be wrong." But in spite of that, he published ours, and we are most appreciative.

Since we first presented our results at three geological meetings,[3,4,5] starting in early 1979, about 12 other groups have entered the field. The latest one to be heard from is a Russian group.

EXTRATERRESTRIAL CAUSE FOR THE CRETACEOUS-TERTIARY EXTINCTION: EXPERIMENT AND THEORY

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Fig. 1. Title page of Lawrence Berkeley Laboratory Report 9666.

Now, for the "what" category on the checklist. We have very strong evidence that an asteroid, (and here is what it looks like,) [Fig. 2] hit the earth 65 million years ago at a velocity in the range of 25 kilometers per second. You may wonder how we got this picture of an asteroid that hit the earth 65 million years ago. This is actually a picture of Phobos, the larger of the two moons of Mars. It was taken by the Mars Orbiter, and I was surprised to see that it was pocked with craters. I had always imagined "our asteroid" as being a nice smooth, round thing that ran into the earth, but of course, it must have been bumped into by many, many smaller asteroids and meteorites, so this is what it undoubtedly looked like. Phobos is actually twice the size of "our" 10 kilometer diameter asteroid, but otherwise it looks exactly the same. NASA found from the color of Phobos that it is probably a carbonaceous chondrite, and we have very strong evidence that the asteroid that hit the earth was also of carbonaceous chondritic composition.

When the asteroid hit, it threw up a great cloud of dust, that quickly encircled the globe. It is now seen worldwide, typically as a few centimeter thick clay layer, in which we see a relatively high concentration of the element iridium, that is very abundant in meteorites and presumably in asteroids, but is very rare on earth. The evidence that we have is largely from chemical analyses of the material in this clay layer. In fact, meteoritic iridium is up by nearly a factor of 10^4 from crustal material. So, if something does hit the earth from outside, you can detect it because of this great

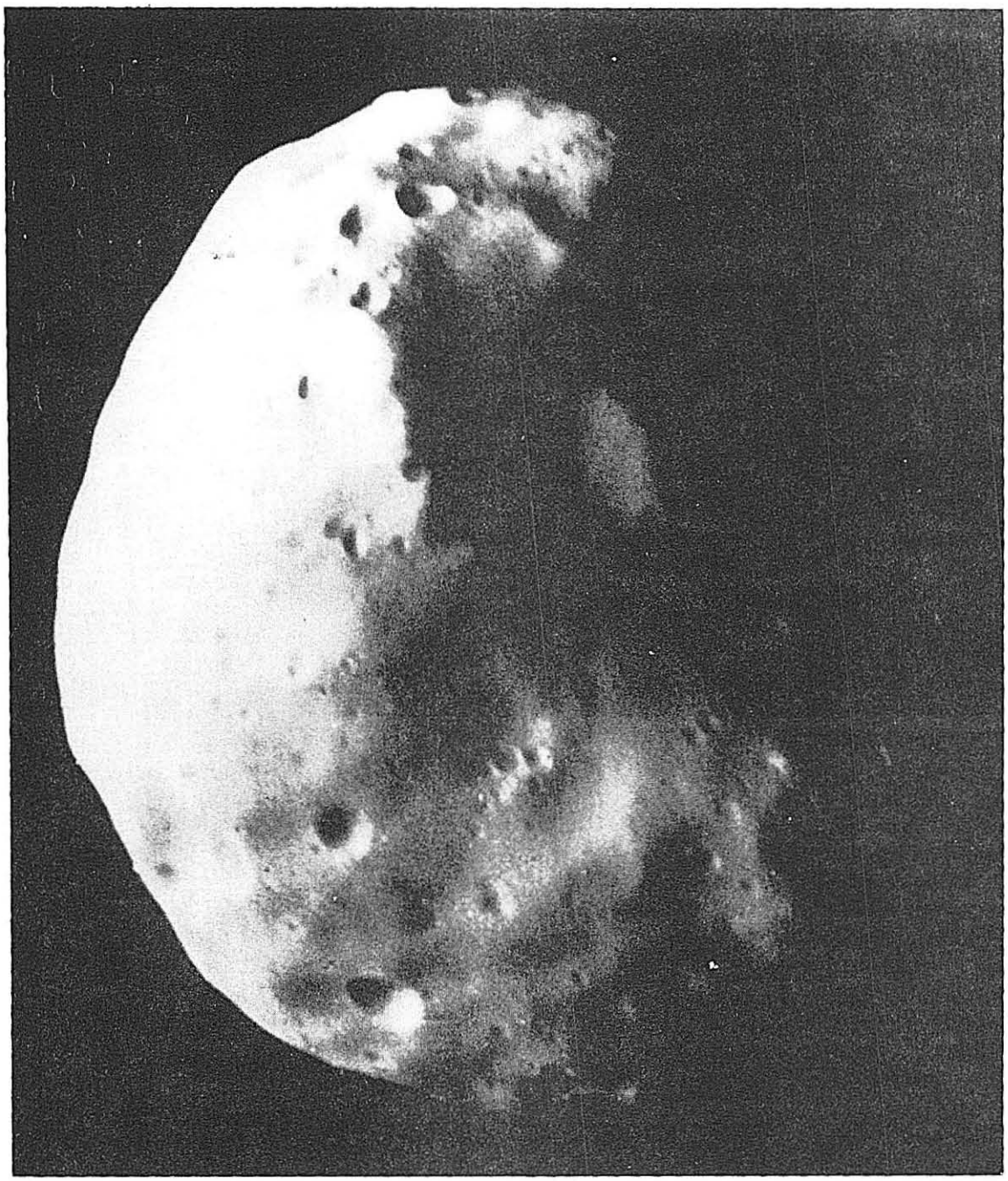

Fig. 2. Phobos, a satellite of Mars. Photo courtesy of National Aeronautics and Space Administration.

enhancement. Iridium is depleted in the earth's crust, relative to normal solar system material, because when the earth heated up, and the molten iron sank to form the core, it "scrubbed out" the platinum group elements, in an alloying process, and took them "downstairs." (We now use the trick of heating our rock samples with molten iron, to concentrate the iridium, and thereby gain greatly in signal to noise ratio.)

Now, we come to "when" on the checklist. There are two time scales for the "when." The first one is the geological time scale, which I now know the way I know the table of fundamental particles, but maybe some of you have not seen it lately [Fig. 3]. Let me call your attention to the fact that the 570 million year time span, from the beginning of the Cambrian up to now, is called Phanerozoic time. That is when there are easily observed fossils in the rocks. Phanerozoic time is divided into three eras, the Paleozoic, or old animals; the Mesozoic, or middle animals; and the Cenozoic, or recent animals. I think the fact that geologists characterize their rocks by the fossils that are in them shows us the close interrelationship between geology and paleontology.

I am going to concentrate most of my attention on this boundary here. It could be called the Mesozoic-Cenozoic boundary, but everyone calls it the Cretaceous-Tertiary boundary and it is 65 million years old. I will also talk briefly about the Permian-Triassic boundary. That is when there was another major extinction. I should say that there have been five major extinctions in Phanerozoic time.[6] I

Geological Time Chart

ERAS	PERIODS (OF TIME) or SYSTEMS (OF ROCK)	EPOCHS (OF TIME) or SERIES (OF ROCK)	APPROXIMATE TIME IN YEARS SINCE BEGINNING OF EACH
CENOZOIC	QUATERNARY	RECENT	
		PLEISTOCENE	1,000,000
	TERTIARY	PLIOCENE	12,000,000
		MIOCENE	30,000,000
		OLIGOCENE	40,000,000
		EOCENE (& PALEOCENE)	65,000,000
MESOZOIC	CRETACEOUS		120,000,000
	JURASSIC		155,000,000
	TRIASSIC		225,000,000
PALEOZOIC	PERMIAN		250,000,000
	CARBONIFEROUS PENNSYLVANIAN MISSISSIPPIAN		300,000,000
	DEVONIAN		350,000,000
	SILURIAN		390,000,000
	ORDOVICIAN		480,000,000
	CAMBRIAN		570,000,000

Fig. 3. Geological time chart of the Phanerozoic Eon.

will also say something about the boundary between the Eocene and the Oligocene which appears here, at about 34 million years ago, accompanied by a less severe extinction event.

Just a month ago, Dave Raup of the Field Museum, and who is in this auditorium today, coauthored a definitive article on the five major extinctions.[7] It includes the next slide [Figure 4], in which the number of extinctions at the family level, per million years, is plotted against time. Such a chart makes me feel right at home, because for a good many years, I was called a "bump hunter"--a particle physicist who looks for "resonances," or peaks that stick out above a distribution of background points. So Dave and I had a lot in common, even before I became involved in a paleontological problem. But the reason I am showing this slide is to remind you that there <u>is</u> a substantial background of extinctions; individual families are going extinct, all the time, for natural reasons quite unconnected with the events that have triggered the five "major extinctions." And those who criticize our asteroid theory of the Cretaceous-Tertiary (C-T) extinctions have known about this background for much longer than I have. But I think that on many occasions, they have, as we would say in physics, confused some background events with events that really belong to the peak. I mention this because I believe that such a confusion has contributed to the present controversy concerning the validity of the asteroid hypothesis. When we point to a number of species that went extinct precisely at the iridium layer, our critics commonly discount those extinctions by pointing to other species that were

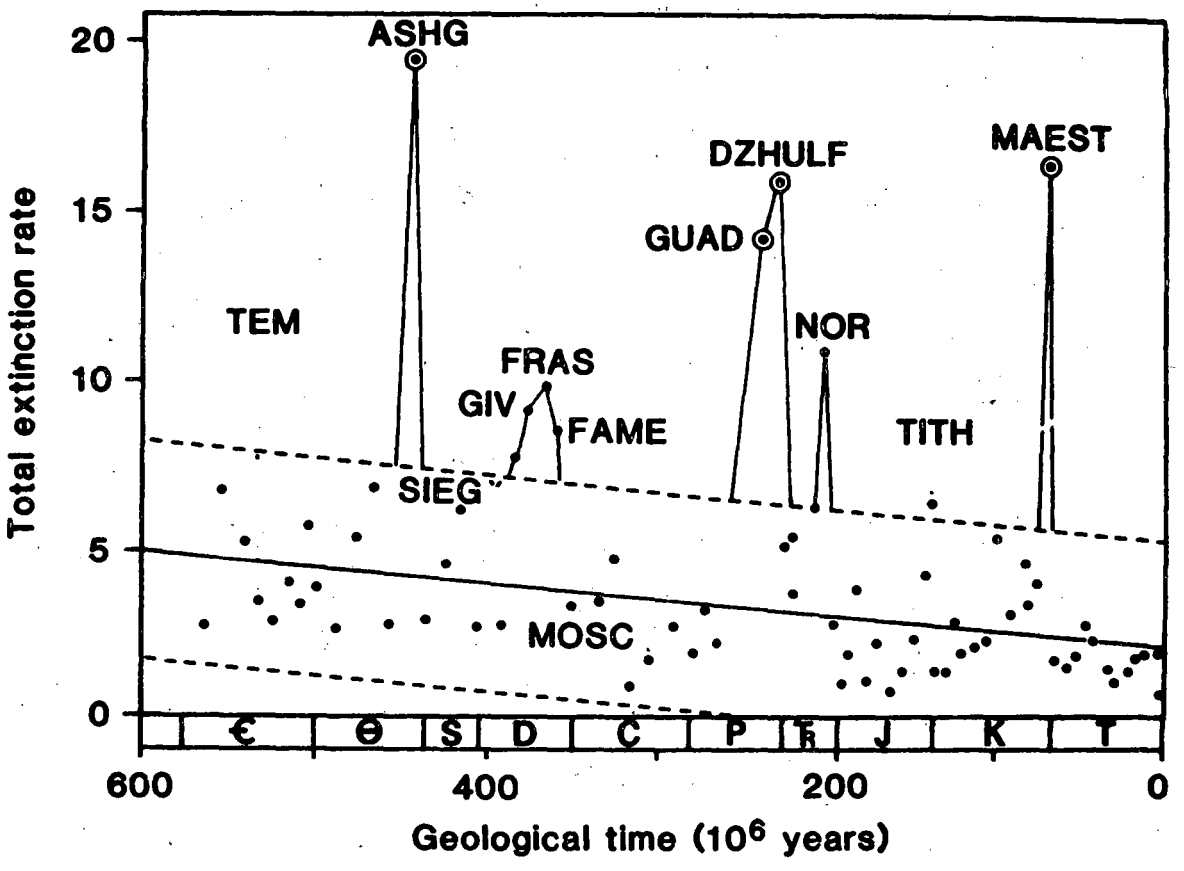

Fig. 4. Total extinction rate (extinctions per million years) through time for families of marine invertebrates and vertebrates. The plot shows five mass extinctions late in the Ordovician (ASHG), Devonian (GIV - FRAS - FAME), Permian (GUAD-DZHULF), Triassic (NOR), and Cretaceous (MAEST) periods. The late Devonian extinction event is noticeable but not statistically significant. Taken from David M. Raup, Science 215: 1501 (1982). Copyright 1982 by the American Association for the Advancement of Science.

obviously "on the way out," just before the asteroid hit. That is what I call "confusing the background with the peak events," and if I didn't direct your attention to this slide, you might find those arguments against our theory more persuasive than the evidence warrants.

So much for the geological time scale. The present time scale is concerned with the discovery of iridium enhancements in the geological record, and with their interpretation in terms of an asteroid impact. We started our search five years ago. We saw our first iridium "spike" four years ago. We were actually looking for iridium, but for the wrong reason, it turns out. The first time we saw the iridium enhancement, we didn't have a complete enough set of rock samples, so Walter went back to Gubbio, Italy, and collected the set whose analysis makes up the points seen in the next slide [Fig. 5]. We plotted that curve, three years ago, and as I said, showed it at a number of geological meetings. This is an unusual diagram, with time plotted upward, in a linear mode in the middle, and logarithmic, at the top and bottom. You see that the iridium concentration, which has been fairly constant for 350 meters below the Cretaceous-Tertiary boundary rises sharply by a factor of about 30 in the 1 centimeter clay layer, and then falls as one goes into the earliest Tertiary limestones. And for the rest of the 50 meters above the boundary, the iridium concentration has returned to the background level we saw in the late Cretaceous limestones.

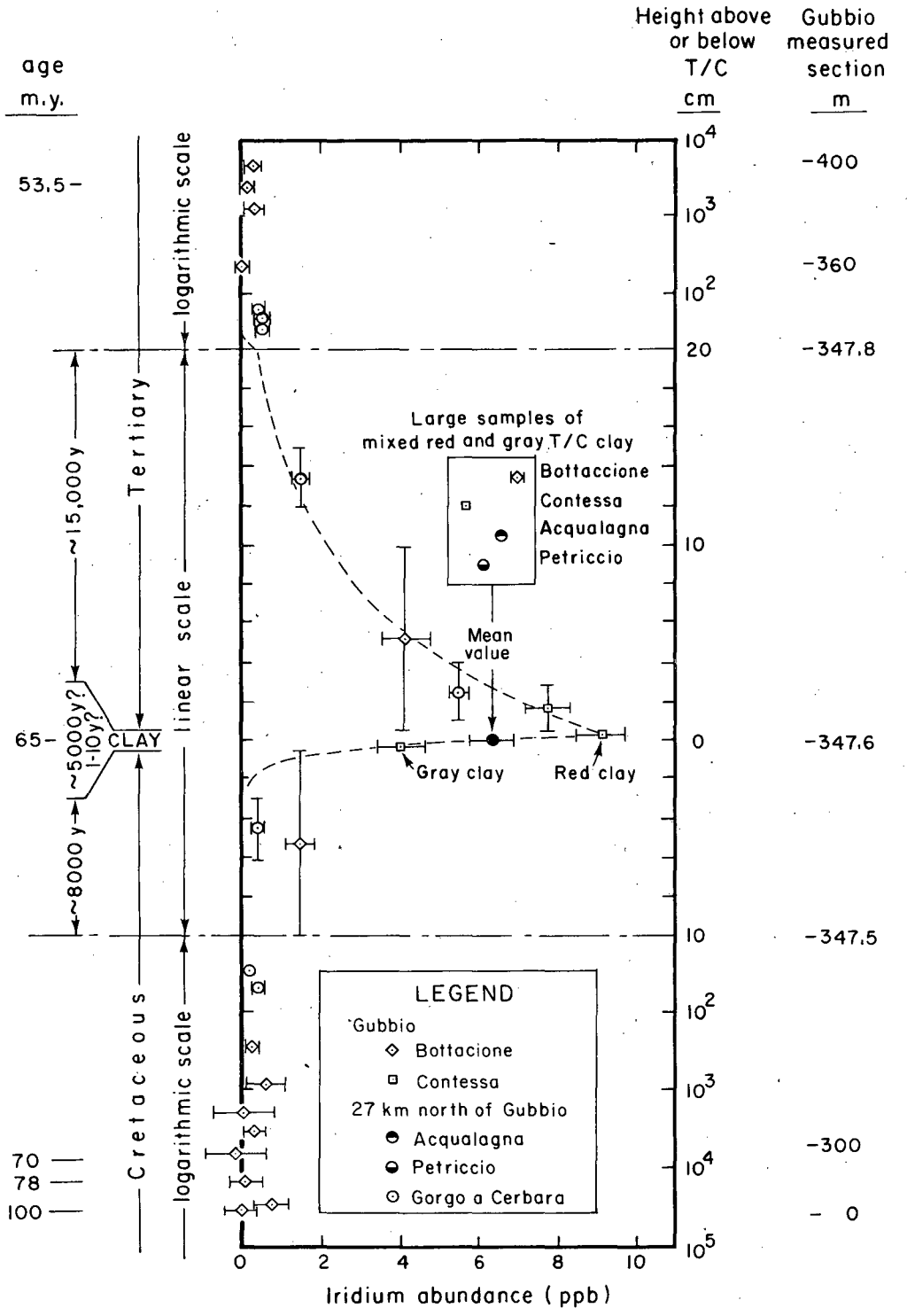

Fig. 5. Iridium abundance per unit weight of 2N HNO_3 acid insoluble residues from Italian limestones near the Tertiary-Cretaceous boundary. Error bars on abundances are the standard deviations in counting radioactivity. Error bars on stratigraphic positions indicate the stratigraphic thickness of the samples. The dashed line is an "eyeball exponential fit" to the data.

This is the very large signal which we explained as being due to the impact of an extraterrestrial object. If I were following the historical approach, I'd give you our original justification for that conclusion. But instead I'll later give you more recent data that show beyond any question that the clay layer contains "undifferentiated" solar system material, with a composition that matches carbonaceous chondrites with surprising accuracy. Our first thought was that the material came from a supernova because some paleontologists believed at that time that a nearby supernova was responsible for triggering the Cretaceous-Tertiary extinction. But we soon showed that the clay was too similar to solar system material to be from a supernova. I sent a letter to Malvin Ruderman, who is a physicist friend of mine and one of the key exponents of the super-nova theory, explaining why we could no longer accept his theory. He wrote back a very short letter saying, "Dear Luie: You are right, and we were wrong. Congratulations. Sincerely, Mal." That is something that made me very proud to be a physicist, because a physicist can react instantaneously when you give him some evidence that destroys a theory that he previously had believed. But that is not true in all branches of science, as I am finding out.

So, three years ago we had this graph and this theory. We wrote it up, and it was published in Science in June 1980.[2] Now, a little more on the "when". Since our original work, there have been three conferences on the subject, because it is such a rapidly evolving field. The first conference[8] was held about one year ago in Ottawa

under the sponsorship of the National Museums of Canada; about 25 people were there, people who study meteorites, impact craters, geology, paleontology, and quite a range of subjects, and we had a very good three-day meeting.

Last fall there was a four-day meeting[9] at Snowbird, Utah. It was sponsored by the Lunar and Planetary Institute, and by this Academy. One hundred and ten people attended that meeting, which lasted four days. They came from more fields than you can imagine, atmospheric modeling, impact dynamics, chemistry, physics, asteroids, and of course, geology and paleontology. We had a very good exchange of views, and almost everyone in this new field had a chance to meet "all the players." More recently, this past January, there was a day-long seminar[10] at the Washington, D.C. AAAS meeting, when all of the invited papers were on this subject.

Now, the "where." The iridium enhancement was first seen near a little town called Gubbio, which is in North Central Italy. It is directly north of Rome and directly east of Siena in the Apennines. The rocks there were laid down as limestone on the bottom of the ocean from 185 to 30 million years ago, and then a few million years ago they were raised up in the mountain building process. They were then eroded by running water, and engineers built roads up through the canyons that fortunately allow someone like me, who is an armchair geologist, to get there in comfort. I found I could get out of the car with a geologist's hammer and break a new surface of the rock and

look at the little creatures that lived there and see how they changed with time.

It is really dramatic to observe the little things called foraminifera which are shelled creatures about 1 millimeter in diameter [Fig. 6, lower half]. You can see them with a hand lens literally by the thousands, right up to the boundary at apparently constant intensity and then without warning, they are gone, right at the clay layer. It was really a catastrophe. They were suddenly wiped out. The only forams that escaped extinction were the tiny species Globigerina eugubina that can be seen in the thin section, above the boundary line in the same figure.

Here is what the rocks look like [Fig. 7]. Walter has his hand on the clay layer and in the next slide [Figure 8], you see a close-up view of the layer, with an Italian coin about the size of a U.S. quarter to indicate its thickness. This layer was deposited 65 million years ago, and it is seen many places worldwide. We took it upon ourselves to analyze the layer by neutron activation analysis, looking particularly for iridium. You have already seen the iridium enhancement, which surprised us so greatly when we first saw it in 1978.

The limestone in this region is about 95% calcium carbonate, and about 5% clay. The calcium carbonate comes from the shells of the little animals that live in the ocean, and fall to the bottom when they die. The clay is washed down from the continents, and carried out to sea by river currents. The two components fall to the ocean floor, where they are compacted to form the limestone.

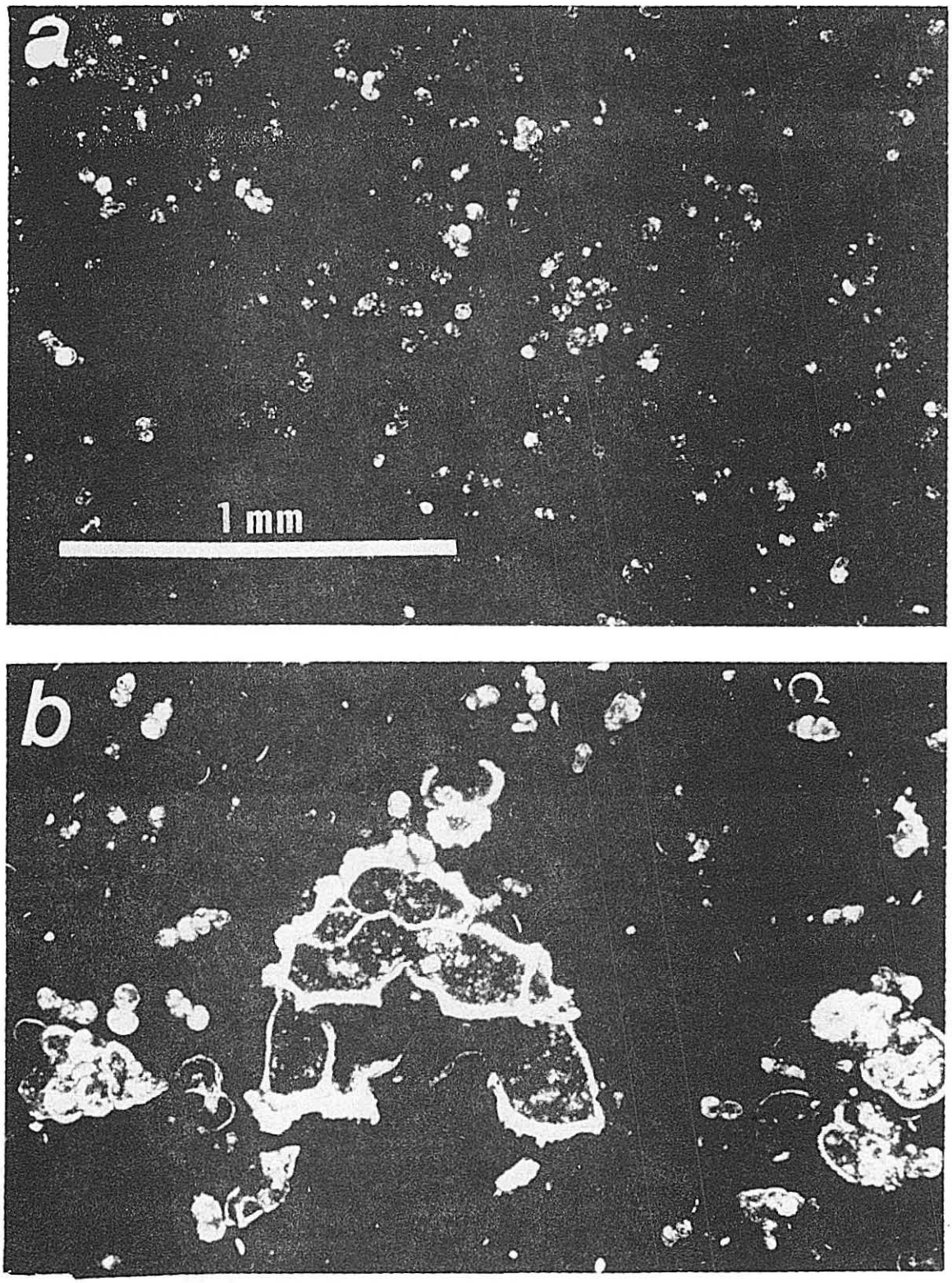

Fig. 6. Photomicrographs from the Bottaccione Section at Gubbio of (a) the basal bed of the Tertiary, showing Globigerina eugubina, and (b) the top bed of the Cretaceous, in which the largest foraminifer is Globotruncana contusa.

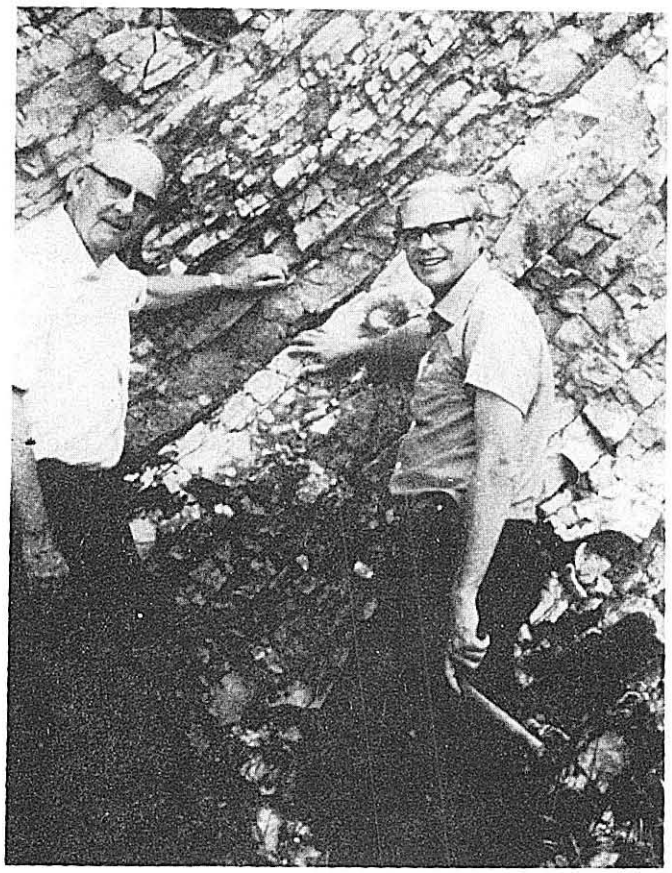

Fig. 7. L.W.A. (left) and W.A. pointing to the Tertiary-Cretaceous boundary in the Bottaccione Gorge near Gubbio, Italy.

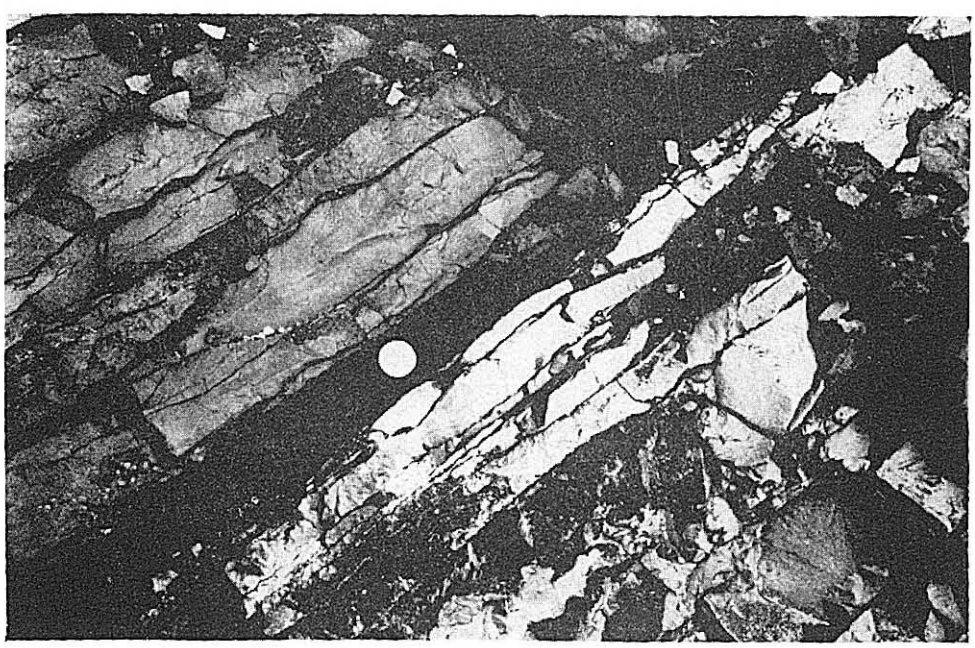

Fig. 8. Close-up of the Cretaceous-Tertiary boundary with a coin (similar to a U.S. quarter) indicating the size of the boundary.

It was generally assumed before we did our work that the clay in the layer was of the same origin as the clay in the limestone, but that turns out not to be the case. After we had seen the iridium in the layer, and concluded that it came from an asteroidal impact, we made our first prediction--that the gross chemical composition of the clay layer would be substantially different from that of the clay in the Tertiary and Cretaceous limestones above and below the layer and that these latter two clays would be essentially identical. We published measurements in our Science paper that showed that this first prediction was verified.

Our second prediction was that the iridium enhancement would be seen worldwide. We had only seen it at that time in one place in Italy, in a valley near Gubbio. We knew that the extinctions were worldwide. So, we guessed and predicted that the iridium would be seen worldwide and in fact it is. Before we published our 1979 paper, we had samples from Denmark which Walter collected, and also some from New Zealand that Dale Russell was kind enough to give us. Both of those showed a nice iridium enhancement. Both enhancements were bigger than the one we saw in Gubbio. In fact, when you look at this world map [Fig. 9], you will see that we first discovered the iridium in nearly the hardest place to find it, where the iridium concentration is quite small, compared to most places. This map shows the state of the discovery and measurement of iridium enhancements worldwide as of today. The number attached to each site is the measured nanograms

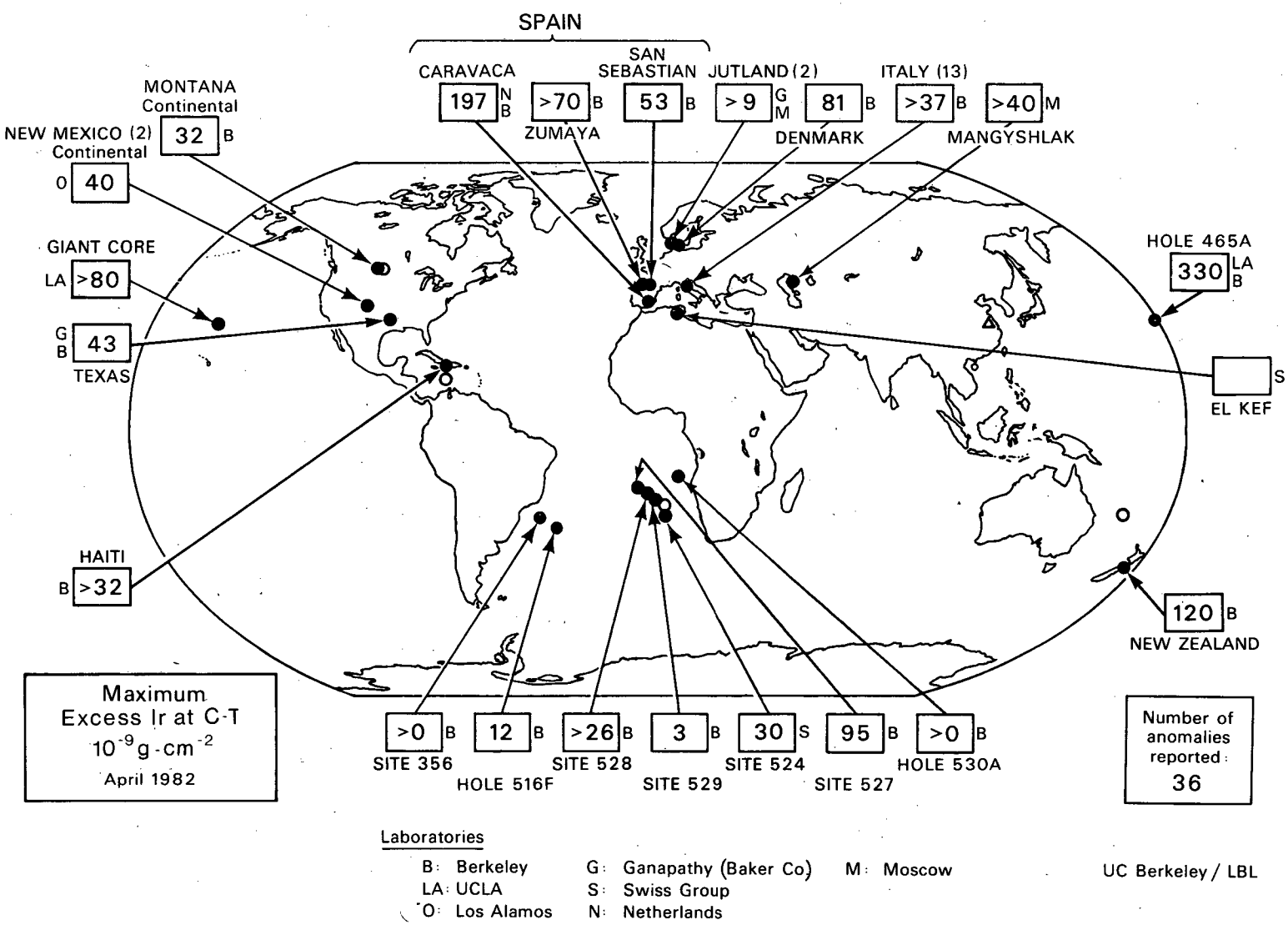

Fig. 9. Map of the world with locations of iridium anomalies.

per square centimeter of iridium at that location. This is of course the area under the curve of the type I showed earlier [Fig. 5, see p. 13].

At the present time there are over 36 locations where the iridium has been found. With one exception the iridium has been found every place that has been thoroughly looked at by our laboratory. Whenever a paleontologist says, "This is the C-T boundary," one of the groups now looking for iridium collects some rock samples, and finds the iridium enhancement, using neutron activation analysis. The one place where this is not true is in Montana. We have two sites in Montana where there are abundant dinosaur fossils. But it is not so easy to pick out the C-T boundary, and there isn't any obvious clay layer. (The clay layer is seen in nearly all the marine deposits) In one of these Montana sites, we have iridium, but we haven't found it at the other site, even after two summers of sample collecting. So, it is almost correct to say that at every identified C-T site that anyone has looked at, iridium has been found. In all of the pelagic or ocean-based sites, the iridium was laid down on the ocean floor 65 million years ago, and it has been found in all our studies within 10 cm and often within 1 or 2 centimeters of the place where the paleontologists said we should look.

I think it is interesting that after seeing the iridium at one site in Italy, we predicted that it would be seen worldwide at the C-T boundary, and that prediction has been fulfilled, as this map shows.

You will see that there are sites in both the oceans, where deep sea drilling cores have been made available to us, and to other

groups. The largest amount (in the North Central Pacific) is 330 nanograms per square centimeter.

As a physicist, I had expected that when we got a map like this, we would be able to draw lines connecting places with equal grammage of iridium, and then we would be able to mark the center, as on a contour map, and say, "This is where the asteroid hit." But that isn't the way things work in the much more complicated world of geology.

That is the present status. We recently heard that the Russians have a sample with 40 nanograms per square centimeter near the Caspian Sea, and that word came just in time to make this "latest edition" of our world map.

Now, we come to "why," the last item on the checklist--why did we study it in the first place? I don't really have to explain that to an audience of this kind. If I did, I would probably use George Mallory's famous response as to why he tried to climb Mount Everest, "Because it is there." But if I wanted to get more serious, I would say that all of a sudden a few years ago, the four of us realized that we combined in one group a wide range of scientific capabilities, and that we could use these to shed some light on what was really one of the greatest mysteries in science--the sudden extinction of the dinosaurs.

I won't try to tell you how many species or genera went out, 65 million years ago. I get a different set of numbers from every paleontologist I talk to, but everyone agrees that it was simply a

terrible catastrophe. Most of the life on the earth was killed off; about half of all the genera disappeared completely, never to be seen again.

Let me just say a word about the disappearance of the dinosaurs. They were reptiles, and the land reptiles went out in a really catastrophic way. In all, there were several orders of reptiles that disappeared completely at this time, including giant marine reptiles. Those of you who are not familiar with taxonomy will perhaps have forgotten that normally one talks about an extinction at the species level. The passenger pigeon disappeared in the last century. The condors are probably going out soon. Each of those is a species extinction. Above that we have a genus or many genera; above that comes the family; above that is the order and, for fauna, the only higher taxa are class and phylum. So you can see that an extinction that suddenly wiped out several orders was a spectacular catastrophe--not to be attributed to some ordinary environmental change, as some of my friends would want you to believe. Dinosaurs were some of the biggest animals that ever lived on the land, Tyrannosaurus rex for example. There were large reptiles in the seas--the plesiosaurs. There were large reptiles that were flying around in the air--the pterosaurs. All disappeared suddenly, never to be seen again. I simply do not understand why some paleontologists, who are really the people that told us all about the extinctions, and without whose efforts, we would never have seen any dinosaurs in museums, now seem to deny that there

ever was a catastrophic extinction. When we come along and say, "Here is how we think the extinction took place," some of them say, "What extinction? We don't think there was any sudden extinction at all. The dinosaurs just died away for reasons unconnected with your asteroid." So my biggest surprise was that many paleontologists (including some very good friends) didn't accept our ideas. This is not true of all paleontologists; some have clasped us to their bosoms and think we have a great idea.

Now, you have had an overview of the situation to which I should just add one point. Dinosaurs did last for nearly 140 million years from the early Mesozoic, which is sometimes called the age of reptiles, and we believe that had it not been for the asteroid impact, they would still be the dominant creatures on the earth. We would not be sitting here. At least we would not look like we do; it has been suggested that we would have distinctly reptilian features.

I'll now give you a few odd facts that don't fit into the checklist that I started out with. One is that "earth orbit crossing asteroids" are studied by two groups of people; one looks at them as astronomical objects using Schmidt cameras, on whose photographic plates, the asteroids appear as streaks, moving relative to the background stars. The other group studies craters, either on the moon or on the earth. There is some overlap in these two populations. For example, Eugene Shoemaker is an expert in both of these fields.

All of these people agree that there is a power law relationship between the mean time between collision of an asteroid of a given size,

and its diameter, and that relationship is that the mean time to collision is roughly proportional to the square of the diameter of the object. These two groups of people also agree on the absolute numbers. What they say is that an object 10 kilometers in diameter should hit the earth every 100 million years on the average. If you drop the size by a factor of 10, to 1 kilometer, then you drop the mean time to collision by a factor of 100, to 1 million years. If you go down to 100-meter objects, then they hit the earth about every 10 thousand years. That power law goes over an enormous range of sizes. It has been verified on the moon, where you can see very small craters. On the earth, these little ones have been eroded away, or the objects burned up in the atmosphere, so you can only see the big ones.

Now there have been, as I said, five major extinctions in the last 570 million years, and our third prediction was that all of these would turn out to be caused by the same mechanism, an asteroid collision. That is one prediction that has not turned out to be true, but it does have an element of truth, as we'll soon see. We have only looked at one other of the five major extinctions. That is the Permian-Triassic. It is hard to sample, because the best sites are in China. Frank Press, working through our National Academy and the Chinese Academy helped us get one of the two sets of samples of Permian-Triassic rocks that we've analyzed. There is a clay layer between the limestone-like rocks at the P-T boundary. We felt sure that there would be lots of iridium there. But there is not any that we can see. However, we are

very intrigued by the existence of that layer, whose basic chemistry is quite different from that of the rocks above and below it. The fact that it exists was not widely known until quite recently; Walter learned about it less than three years ago. Our present best guess is that it is of volcanic origin, but it might be consistent with the idea that the layer was laid down by a cometary impact. Comets can go much faster than asteroids and can in fact have 50 times the specific energy. So a comet could throw the same amount of dust into the atmosphere, and do the same damage, while bringing in only 1 percent as much iridium. That factor of 100 comes from the increased impact speed, squared, times perhaps a factor of 2 because a comet is typically half composed of ice. That is simply one possible working hypothesis. There is no proof for what I've just said. But if it does turn out to be true, then we will know that the C-T extinction was due to an asteroid, and not a comet, as some of our friends are calling it. At this point, I think the distinction is of no importance; the important conclusion is that a large chunk of undifferentiated solar system material hit the earth, 65 million years ago, and triggered a major extinction.

But I should say that our prediction, although not confirmed in the Permian-Triassic case did lead to another case where there is a coincidence between an iridium layer and an extinction, although not one of the five major ones. Some people say, "I'll bet there are lots of iridium layers all over the place, so there is no reason to say that the oceanic and terrestrial iridium layers are synchronous." But in

my view, that is an exercise in grasping for straws, because it turns out that there are very few iridium layers. No one has yet made a systematic search through all of geological time, but two groups have systematically searched a total of 23 million years of sediments, and found not a single iridium enhancement in this randomly selected 4% of Phanerozoic time. One group, led by Frank Kyte and John Wasson, of UCLA, has searched through the lowest 15 million years of the Tertiary limestones, and the other group, led by Carl Orth of Los Alamos, has searched through 8 million years of the late Devonian.

But we found a very definite iridium enhancement in the Caribbean Sea, at the Eocene-Oligocene boundary,[11] 35 million years ago, and it was independently found by R. Ganapathy,[12] of the Baker Chemical Company. But both of our groups looked there because that boundary coincided with a known layer of microtektites and with a lesser extinction event. That was very exciting to us because shortly before we did this work, Billy Glass, a leading expert on microtektites, and his collaborators, had shown that these microtektites--part of the "North American strewn tektite field"--extended more than half way around the world.[13] And here again, "everybody," (all but one person), believes that tektites are due to the impact of large meteorites (or small asteroids) on the surface of the earth. Also, Billy Glass points out that at the tektite "horizon," there was an extinction of several species of radiolaria, much like the forams I talked about earlier, but their chemistry is siliceous, rather than calcareous. [Note added in proof. In collaboration with Billy Glass, we have

recently found three new and quite substantial iridium enhancements at the Eocene-Oligocene tektite horizon in deep sea drilling cores from the Gulf of Mexico, the Central Pacific, and the Indian Ocean].

So, we now have several different bits of evidence that tie impacts to extinctions. We have the iridium layer at the tektite layer and we have the extinction of the radiolaria at that same time. So, although we did not find any iridium at the Permian-Triassic bounday, we did find another iridium enhancement coincident with an extinction, and at the present time there are only two known stratigraphic levels where there is a sudden excess of iridium, seen in more than one location. I'll conclude this section of my talk, that connects extinctions with impacts, by saying that the theory seems to be holding up very well on that score, and our third prediction can be considered to have been partially confirmed. Asteroid impacts have produced more than one extinction, but not all five of the major ones.

Now, let me talk about prediction number four, that there should be an iridium enhancement on the continents as well as on the sea floor, at the C-T boundary. A lot of people were saying, two years ago, that the reason we found iridium in the sea floor deposits was that some change in ocean chemistry, 65 million years ago, precipitated out the iridium that was dissolved in the ocean. We had given two arguments in our paper as to why that was not so, but we could not prove it conclusively. We asked one of the national funding agencies for money to search for iridium in Montana, alongside the dinosaurs,

and one of the peer reviews that came back said, in effect, "These guys would be wasting their time and your money if they did this job, because the iridium came out of the ocean and therefore won't be seen in continental sites." But fortunately we were able to do it anyway; we went up to Montana and looked for iridium. But before we got our first iridium there, Carl Orth from Los Alamos and his colleagues discovered that there was iridium at a continental site in New Mexico.[14] I think this was a very important discovery, and I want to show you Carl Orth's curves.

Here are the curves [Fig. 10]. In the lefthand side of the diagram you'll see the depth in meters. They drilled a hole in the Raton Basin, in New Mexico, and tested the rocks with neutron activation analysis, with a higher sensitivity than anyone else has attained. The surprising thing is that this is a logarithmic scale of iridium abundance. The iridium suddenly goes up by a factor of 300 precisely where the paleontologists told them to look. That was a very exciting thing because that showed that the iridium didn't come out of the ocean. It was deposited on the continents, as well as on the ocean floor, as called for by our prediction number four. So the Los Alamos discovery added great strength to our theory, as far as some of its critics were concerned. I should add that we weren't surprised, because we thought the arguments we had given against an oceanic source of the iridium were quite valid.

Now, just a few days before I saw Carl Orth's preprint, which he kindly sent me, I had read a paper[15] by Leo Hickey, who is a

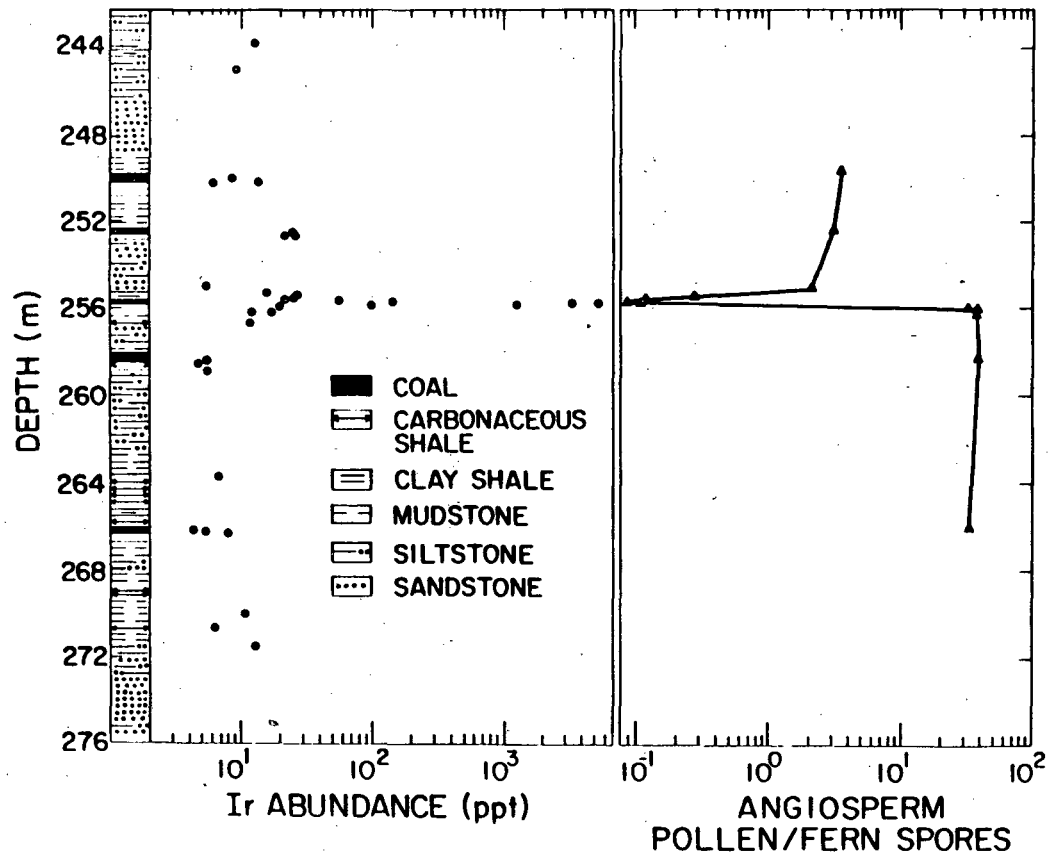

Fig. 10. Iridium abundances (solid circles) and ratios of angiosperm pollen to fern spores (triangles) as a function of core depth and lithology. The surface Ir density is $\sim 4 \times 10^{-8}$ g cm^{-2}. Reprinted from Los Alamos report LA-UR-81-2579.

paleobotonist here in Washington and who has been one of our most vocal critics. He is also a very good friend. Walter went to graduate school with him and they have been close personal friends ever since. Leo's paper in Nature was entitled "Land Plant Evidence Compatible with Gradual, not Catastrophic, Change at the End of the Cretaceous." He wrote this paper after seeing all the evidence that we presented, and I couldn't find anything in it that made me feel that he was ignoring our evidence; he was just looking at a different data base, and coming to a different conclusion.

His abstract ends with this sentence: "However, I report here that the geographically uneven and generally moderate levels of extinction and diversity change in the land flora, together with the non-synchroneity of the plant and dinosaur extinction, contradict hypotheses that a catastrophe caused terrestrial extinctions." So, his considered opinion after studying all the evidence and looking at what he saw in the plant record convinced him that we were wrong. He says quite clearly that there was no effect of a catastrophe on the plants. And as I just said, when I read his paper, I had no evidence that directly contradicted his conclusions.

So, you can imagine my excitement to see Carl Orth's right hand plot. This is the number of pollen grains per cubic centimeter plotted against stratigraphic height, and normalized to the fern spore count. The interesting thing is that the pollen count drops by a factor of 300, in precise coincidence with the iridium enhancement. I

must say that this looks to me like a catastrophe, and in fact, several pollen types disappear from the record at this point. If we look at the next slide [Fig. 11], we see that the resolution of the pollen fall-off is undoubtedly limited by the sample thickness of 2 centimeters. The drop-off of a factor of 300 occurs from one rock sample to the next, and my guess is that the discontinuity is even more precipitous than this graph shows. This is by far the sharpest resolution that paleobotanists have ever seen, as far as I can learn, and it is not surprising that it has been missed in the past, just because of its sharpness. (And it confirms prediction number 5 that we made in our paper---there would be an extinction of plants in coincidence with the iridium layer, on the land.)

And to show that the missing of a "sharp spike" is not peculiar to paleobotany, let me remind the physicists in the audience how the Psi meson was discovered at Stanford several years ago. The SLAC-SPEAR electron-positron colliding ring had been operating for some time, without finding anything "very interesting." It was exploring new territory, and the physicists were looking for enhancements in the counting rate, ("bump hunting") by stopping every 100 Mev--equivalent in paleontology to taking a sample every meter. They were unhappily coming to the rather firm conclusion that there were no new "resonances" in this energy region; such resonances were expected to be more than 100 Mev wide. But as a result of some excellent detective work, paying attention to the slimmest of clues, the SLAC-LBL group looked between a pair of 100 Mev "milestones," and discovered

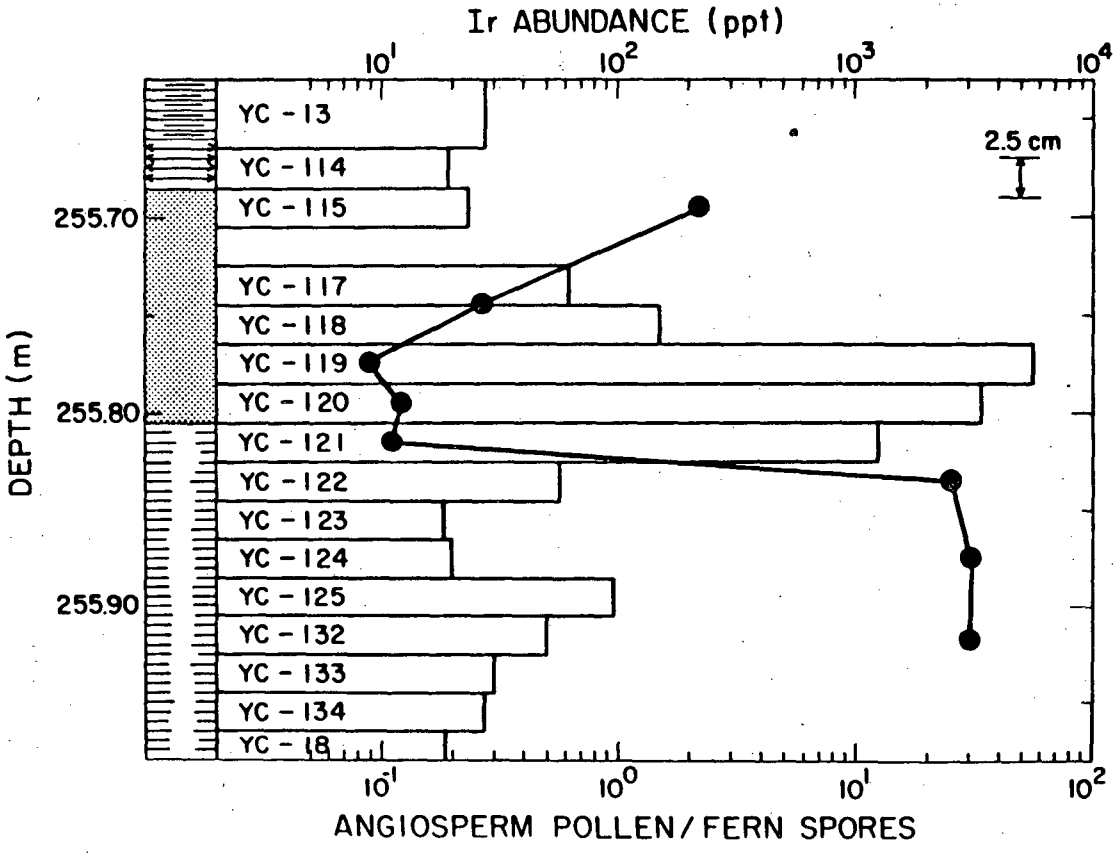

Fig. 11. Expanded view of Fig. 10 in the vicinity of the iridium anomaly and the pollen break. The Ir abundances are given by the histogram and the angiosperm pollen/fern spore ratios by the solid circles. The lithologic symbols are the same as in Fig. 10 except for coal, which is shown by stipple. Reprinted from Los Alamos report LA-UR-81-2579.

the extremely narrow Psi resonance, that sent the counting rate up by more than a factor of 100, within the space of a single Mev, and within an observing time interval of 2 hours. This discovery sent Burt Richter to Stockholm with great promptness, but the important point I want to make is that after those two hours of excitement at Stanford, no one ever said again that there was nothing interesting going on in that wide energy range, that had for so long been certified as "uninteresting." The Psi "bump" from then on was a part of the lore of physics.

But Leo Hickey has behaved quite differently with respect to the "narrow spike" discovered by Carl Orth, and in fact, he simply ignores it. Here is what he said in his invited talk last January, at the annual AAAS meeting[10] some months after he learned of the Orth discovery at the Snowbird conference. After repeating the conclusions of his Nature paper, that the pollen spectra showed no evidence for a catastrophe, he said, "Every pollen spectrum that has come in since this chart was plotted tends to corroborate these data." You can imagine my surprise when I heard this. So I suggest you take a good look at this narrow "glitch" in this pollen spectrum, and remember it the next time you hear our friend Leo say that the plants didn't notice the asteroid impact. (My own guess is that before long, this graph will be reproduced in every textbook on geology and paleontology.)

I consider Carl Orth's important paper to be a confirmation of three separate predictions or deductions we made in our Science paper.

Number 4 was that the iridium would be found on the continents as well as on the ocean floor; number 5 was that the plants would suffer simultaneous extinctions, just as the animal life had. And number 6 was that the iridium didn't come from a supernova.

Leo Hickey asserted in the abstract I quoted that the plant and dinosaur extinctions were "non-synchronous" but I think I will soon convince you that he was wrong in saying that.

Science has published in the last year three separate reports on the state of the asteroid theory. They were all written by Richard Kerr, and the first one was entitled "Asteroid Theory of Extinction Strengthened."[16] We thought that was a very nice title, but then when we read through it, we found there were interviews with lots of people who thought that we were wrong for a number of reasons. I thought the strangest of these was one that said that we found too much iridium in the Danish clay layer. Several experts on cratering were quoted as saying that we should not have found nearly that much iridium because when the asteroid hits, the material going up into the stratosphere should be not only that of the asteroid, but diluted with 1000 to 10,000 times the mass of the asteroid. Richard Grieve of the Department of Energy, Mines and Resources, of Canada was quoted as favoring the figure 1000, and Tom Ahrens of Cal Tech was said to prefer 10,000. We had used a factor of 60 dilution in our paper, which we had gotten in fact, from Richard Grieve over the telephone a few months earlier. So we were surprised by Dick Kerr's Science

report. It turned out later that both of these gentlemen's remarks had been misinterpreted. They both had said that the material close in to the crater would be diluted by these very large factors, and that ties in well with what we know about Meteor Crater in Arizona; there is very little meteoroid material close to the crater. But both men agreed that the material that was sent high up and would be spread worldwide would be diluted by 20 to 100 times, right in line with what we observed. So, that was a major challenge which the theory met and in the process, came out stronger. Everybody (no quotation marks) now agrees that the iridium concentrations we find are okay, from the standpoint of the asteroid impact hypothesis.

Then there was another report to the readers of Science by Dick Kerr, entitled "Impact Looks Real, the Catastrophe Smaller."[17] This came after the Snowbird meeting in November 1981, and indicated that a consensus had formed in favor of the asteroid theory. There, we had come up against a really serious challenge, involving good science, where the new numbers were in serious disagreement with the corresponding ones we had used in our Science paper. We had said that the time for the dust to fall out of the stratosphere was about three years, which gave it time to spread slowly across the equator; it spreads very rapidly across all longitudes, near its original latitude. We based our numbers on the observations we found recorded in a thick volume published by the Royal Society[18], soon after the volcanic explosion of the island of Krakatoa, in the Dutch East Indies, in 1883.

But at Snowbird, Brian Toon, of NASA Ames, said the dust would fall out in 3 to 6 months,[19] so our mechanism for getting it from one hemisphere to the other wouldn't work. We were therefore in very serious trouble, except for one comforting fact--we had already seen the iridium layer worldwide, so we knew there had to be a transport mechanism.

I'll now tell you how the Royal Society went wrong, almost a hundred years ago, and how we recovered from that mistake. Professor Stokes, of Stokes Law fame, measured the size of the dust particles by the angular diameter of their diffraction rings, and calculated the time of fallout to be 2 to 2.5 years, in agreement with the duration of dusty sunsets that were seen worldwide. We took his word for it. We said we thought "our" (much more copious) dust would stay up about three years. But more recently people have found that the dust falls out much more quickly than that, because the dust particles grow by accretion, and as Stokes' equation predicts, fall faster. So, after Krakatoa, the "dusty sunsets" were at first made by the dust, but it fell out in 3 to 6 months. And unknown to Prof. Stokes, the job of making the sunsets dusty was smoothly taken over by the much finer aerosols that accompany volcanic eruptions, but not impact explosions. They did their work for the next two years, but Brian Toon correctly pointed out that we couldn't use such aerosols to keep it dark, 65 million years ago.

We knew there had to be a mechanism to get the dust spread worldwide, but our original idea that it was spread through the

stratosphere went down the drain. It takes something over one year for material suspended in the atmosphere to move from the northern hemisphere to the southern hemisphere. The Russian hydrogen bomb tests in the 1950's made a lot of carbon 14, and that was observed to move from the northern hemisphere to the southern in about one year. So, if the dust fell out in 3 to 6 months, it could not get from one hemisphere to the other. But we had already seen it in both hemispheres. So something was wrong. Fortunately, the next day at the Snowbird Conference, two reports came in that said that the material got spread not by stratospheric winds but by either of two much faster mechanisms.[20,21] In the case of Eric Jones and John Kodis at Los Alamos, they showed the material actually went into ballistic orbits and was spread worldwide in a matter of hours. We had known, of course (from a back of the envelope calculation), that there was enough energy brought in by the asteroid to put the observed material into ballistic orbit, but we could not think of a detailed mechanism that would accomplish that feat. We did not see how you could get the little particles up through the atmosphere, but people at Los Alamos and Cal Tech both used very large computers, and ran a simulation of an asteroid coming down and hitting the earth. It turned out that convective vertical winds in the fireball did the job. They analyzed a cylindrical asteroid coming vertically downward; the symmetry introduced in this way simplified the calculations. Both groups showed that when the asteroid hit, it would distribute the material worldwide very

rapidly, as we saw it distributed, and that it would be diluted by between 20 and 100 times its incoming weight--also as we had seen. I won't try to enumerate the predictions and their fulfillments that are associated with the saga I've just recounted, but I find the whole thing very supportive of our theory.

So, all of a sudden everything was in great shape. The computers did not know that we were in trouble, but they got us out of it very nicely. It turned out that Tom Ahrens and John O'Keefe, who did their work at Cal Tech, were actually wired in by a special line to the Berkeley computer. That computer was down in the basement of our building, cranking away on this problem of great interest to us, and we didn't even know it.

Now, for a couple of other odd facts. Miriam Kastner of the Scripps Institution of Oceanography has shown that the boundary clay layer in Denmark was a glass 65 m.y. ago which resulted from a volcanic or impact eruption.[22] Jan Smit has found, in Spain and Tunisia, large numbers of very unusual, tiny "sanidine spherules" embedded in a very narrow iridium-bearing clay layer at the C-T boundary.[23] He argues from these that the layer is either of impact or volcanic origin, and since the relative abundances of the rare elements match that of carbonaceous chondrites, but not crustal or mantle material, he concludes that it is of impact origin. These two separate observations confirm our implied prediction, number 7. Alesandro Montanari, a student of Walter's, has also found these same unusual spherules in the Italian clay.

Jan Smit has shown that the sanidine-bearing layer in Spain where he does his work is about 1 millimeter thick, which shows that it was deposited in a period of somewhere between 50 and 300 years (or less). So, paleontologists now have a time marker which is seen worldwide, and which we now know to be laid down in an exceedingly short time, from geological observations. And from the computer simulations which I happen to believe, we know that the layer was laid down even much faster. The so-called hydrodynamic computer programs used in these computer simulations are the ones used to design nuclear weapons, which involve temperatures, pressures and material velocities much higher than those found under normal conditions, and they are known to do their tasks with great precision. A typical computer run involves many billions of numerical calculations. So far as I know, such great computing power has never before been brought to bear on problems of interest to paleontologists.

Now, as far as killing mechanisms are concerned, we had trouble finding our first killing mechanism. We tried lots of places to get the iridium, and if you are interested, you can read about them in our 1979 preprint. But we had to discard all culprits but the asteroid. So finally, we said, "Okay, let us accept the fact that the material that we see worldwide had to fall down through the atmosphere. We now see that it is a few centimeters thick. Let us take that material and distribute it in the atmosphere in any kind of particles and with any spacing that you can imagine. It is going to be very, very opaque." We originally thought it would be black for three years. Now, the

number is 3 to 6 months,[24] and the scenario that we came up with was that the darkness would stop photosynthesis and all the little phytoplankton on the surface of the ocean would die, fall to the bottom, and the food chain for the larger animals in the sea would be disrupted and then on the land, the plants would also die. Herbivores would die of starvation and carnivores would die because they couldn't find anything to eat. That was just the first of several killing scenarios. I'm confident that it is the only one we need to explain the catastrophic extinctions in the oceans. The lack of sunlight will quickly kill the phytoplankton in the surface layers, and when that base of the food chain is eliminated, most of the life in the sea is doomed to a relatively quick death. Hans Thierstein, a paleontologist who specializes in microplankton is comfortable with this scenario.[24] "Darkness is a very good mechanism that could account for the pattern we have."[17] In fact, the micropaleontologists, most of whom like the asteroid impact theory, are much happier with the 3 to 6 months of darkness than they were with the original, longer time scale.

But now we really have more killing mechanisms than we need. Probably each one of them plays some part in the extinctions on land and in the sea.

Historically, the second one is due to Cesare Emiliani, who is a paleontologist, E. B. Kraus, who is an atmospheric modeler, and Gene Shoemaker,[26] to whom I have already referred. They believe that a greenhouse effect caused by the asteroid hitting the ocean and sending up an enormous amount of water vapor would heat the atmosphere and the

environment up by as much as 10 degrees centigrade. That does not seem like very much to me, but they assure us that it would kill a great number of the land animals, particularly near the equator, where the fauna are living close to the maximum tolerable temperature. Then Brian Toon and his colleagues[27] at NASA Ames in California came up with a third killing mechanism. They say that their computer simulations show that it would first be very cold for several months. The temperature would go down to about zero degrees Fahrenheit for 6 to 9 months. That would wipe out most of the animals that did not know how to hibernate. Now, recently, a fourth killing scenario has come to light. This is one from MIT, where Professors Lewis, Hartman and others[28] are saying that the enormous amount of radiant energy in the rising fireball would go through the atmosphere and fix a lot of the nitrogen to make enormous amounts of nitrogen oxides. It would make acid rain, and the rain would fall into the ocean and they believe that the calcium carbonate based forams would dissolve in the acidified oceans. I think the chances are that all four of these scenarios are going to play some part in the various extinctions, and it is going to be a life's work for some people, I am sure, to untangle all these things.

Let me now tell you just how much energy was released when the asteroid hit. A trivial calculation shows that it released an energy of about 100 million megatons. A 1-megaton bomb is a big bomb. This is 10^8 of those. Now, the worst nuclear scenario I have ever heard considered is when all 50,000 bombs that we and the Russians own go off pretty much at the same time. The energy released in that case

would be down by a factor of about 10,000 from what we get in the asteroid impact. So, this asteroid impact is the greatest catastrophe in the history of the earth, of which we have any record, and in fact we have a very good record of it.

I will now comment in some detail on the quite contrary views of the C-T extinction, that have been expressed in print, and in many lectures, by my good friend William Clemens, professor of paleontology at Berkeley, who is certainly the most vocal critic of our work. We have a nice arrangement with Bill. We have spent every Tuesday morning for the past 12 weeks sitting around a table in his conference room, seven or eight of us--four members of our group and Bill Clemens and one or two of his students and Dale Russell, who is on sabbatical leave at Berkeley. Dale is a verterbrate paleontologist whose specialty is the study of dinosaurs. He agrees with us that the dinosaurs were suddenly wiped out as a direct result of the asteroid impact, and he further believes that had the asteroid not hit the earth, 65 million years ago, the mammals could not have evolved the way they did. But he believes that intelligent "humanoids" would have evolved in the class of reptiles. He and one of his colleagues are responsible for a set of pictures that purport to show what these two-legged, upright walking, intelligent creatures might have looked like. And they might have formed their own National Academy and be discussing what would happen to them when one of the asteroids they see in their telescopes hit the earth.

Our little group has sat around the table for three hours each time, and debated our differences and tried to get to understand how the other person was thinking. I don't think this has happened very often across disciplinary lines in science. It is a really good way to settle arguments, even though we still have some pretty serious disagreements. But fortunately, we've remained friends throughout our long period of disagreement.

We are indebted to Bill for getting us samples from Montana that show an iridium enhancement in rocks which are close to dinosaur fossils. Carl Orth's group down in New Mexico found the first iridium at a continental site, but there were no dinosaurs around there. Bill Clemens collected samples for us in his favorite hunting grounds at Hell Creek in Montana, one of the greatest sites for finding dinosaurs. Frank Asaro and Helen Michel found a large enhancement of iridium, and that is the first experimental evidence that ties the asteroid impact to the extinction of the dinosaurs. The next slide [Fig. 12] shows the Montana iridium enhancement. I had given a number of talks to physics department colloquia entitled "Asteroids and Dinosaurs," before we had any direct connection between the asteroid impact and the dinosaur extinction. You might consider that to be one of our major predictions--that the asteroid impact led directly to the dinosaur extinction. I think the connection is now extraordinarily well established, but I'll try to explain why Bill Clemens doesn't agree with that conclusion, and then I'll tell why I think his arguments can't stand up under close scrutiny.

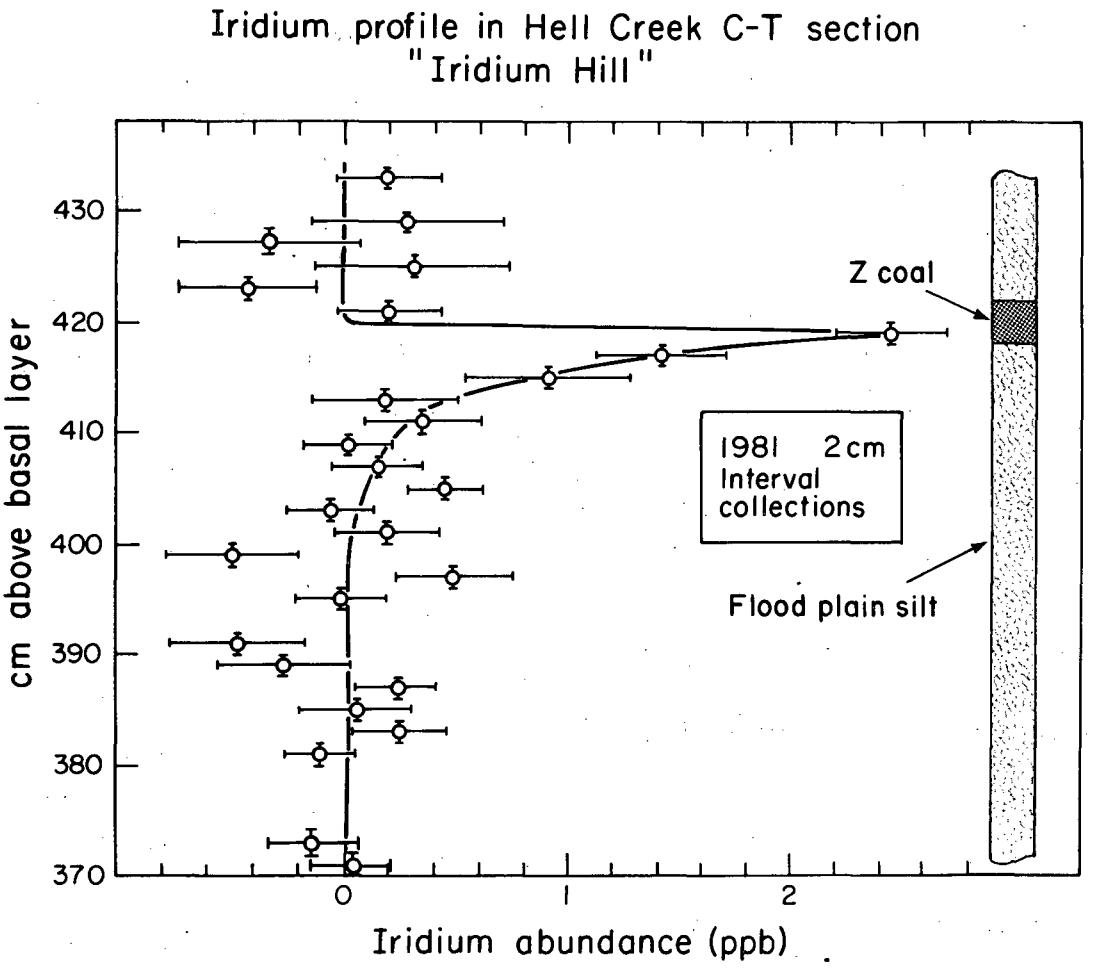

Fig. 12. Iridium abundance at "Iridium Hill" section in Hell Creek, Montana, showing the Z coal.

This is Bill Clemens' slide [Fig. 13] that he has used in a great many talks, and I am indebted to him for letting me use it today. He uses this to show that we are wrong in associating the dinosaur extinction with the asteroid impact. Here is where the iridium was found and it is in what is called the "lower Z coal." This coal layer is seen over wide areas in Montana, and on this diagram it is seen at the 4.2 meter level. Bill says that this (the 0.8 meter level) is the highest dinosaur bone he has seen and he frequently refers to this as the stratigraphic level at which "the dinosaurs became extinct." (In a recent article,[29] he says that his student, Lowell Dingus, has seen some dinosaur fossils above the Z coal layer.) Since this is our main point of contention, I'll spend some time explaining our differing views concerning the significance of that "highest bone."

Two other features of this very important slide are also worthy of notice, the pollen and the fossiliferous zone, which Bill usually refers to as a site which produces Paleocene mammal fossils. I won't speak further of the pollen, which doesn't seem to bother Bill nearly as much as the Paleocene (or early Tertiary) mammal fossils. (These appear at the 2 meter level.) Bill's main interest is in early mammals, rather than in dinosaurs, and he feels that such mammals have no business being below the iridium layer, if that layer really defines the Cretaceous-Tertiary boundary, which he doubts is the case on the continents--although he is apparently able to accept it in the oceanic sequences. During many of our private discussions, I took the position that evolution doesn't move fast enough to make the appearance of

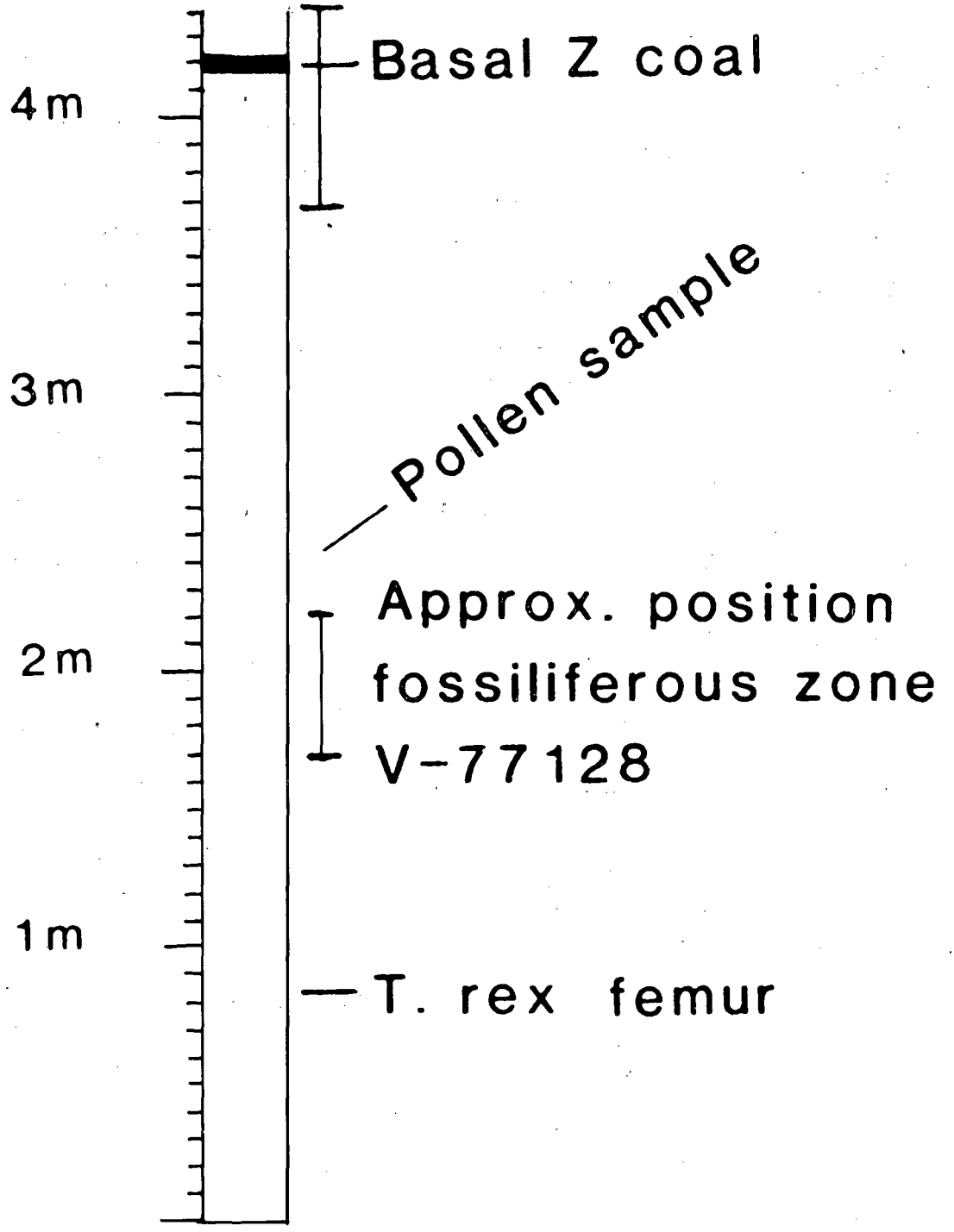

Fig. 13. Stratigraphic section in Hell Creek, Montana.

Paleocene mammal fossils below the iridium layer troublesome to our theory--that the dinosaurs were reproducing at a fairly constant rate, over millions of years, and were suddenly wiped out as a result of the asteroid impact. Paleontologists have never before had such a world-wide sharply defined "horizon," as is furnished by the iridium layer, except for those special cases that happen to coincide with a paleo-magnetic reversal. So my argument (in a field in which I have no credentials) was that there was no previous evidence that the Paleocene mammals didn't originate 20,000 years before the Paleocene period started--at the C-T boundary.

Now let's look at the time scale that applies to Fig. 13. In all our long discussions of this figure, the sedimentation rate was assumed by everyone to be about 1 meter in 9,000 years. (That average rate comes from the known time between the magnetic reversals that are observed in the Montana sections. Since that rate is commonly used, and since none of the arguments I am about to give are in any way dependent on that rate, I'll assume, for reasons of simplicity, that the rate is just 1 meter per 9,000 years.) So Bill Clemens is impressed by the fact that the dinosaurs became extinct "long before" the iridium layer was deposited--a difference in height, on this figure, of 3.4 meters = 30,000 years. But the usual description, by paleontologists, of an extinction that took place in 1 million years, is that it "happened rapidly." To someone like me, who is new to the field, it is confusing to hear from the same people, that 1 million years is a "short time," and 30,000 years is a "long time."

In addition to this strange confusion in time scales, I have heard Bill Clemens, and other paleontologists as well, say that the dinosaurs didn't disappear suddenly, but were declining in population and diversity, all over the world, for a million years or so, before they finally became extinct, near the Cretaceous-Tertiary boundary. First of all, I should say that I have looked closely at a lot of data that bear on this alleged "decline," and I agree with Dale Russell that it doesn't stand up under careful examination. In the last of our 12 seminars to which I've referred, Bill Clemens presented a table of dinosaur fossils that showed that neither the population nor the diversity of dinosaurs had changed appreciably in the 20 meters below the Z coal layer. (At least, that is what the data said to me and to Dale Russell, and Bill Clemens didn't attempt to use them to prove otherwise.) Bill's table appropriately showed only "articulated dinosaur fossils," meaning samples of at least 2 bones in nearly their normal relationship, or a single bone so large that one could be sure that it hadn't been shifted from its original site, by running water, etc. There were 17 fossils in the sample, extending downward from the Z coal to a distance of 60 feet = 18.3 meters. This corresponds very nearly to a time interval of 165,000 years. The average spacing was 1.1 meters per dinosaur, and anyone who is used to looking at truly random samples of objects would say, "There is no indication that the population from which this sample was taken was declining as it approached the Z coal layer." It looks extraordinarily uniform to me, even though there is a non-statistically significant <u>increase</u> in the

number of fossils in the top 30 feet, compared to the bottom 30 feet--10 to 7.

I will return to a more detailed discussion of these matters, because they are the ones that cause me to come to conclusions quite different from those drawn by Bill Clemens. And I'll show that if Bill Clemens is correct in his "decline hypothesis," it destroys his argument that the eventual extinction of the dinosaurs came before the asteroid impact occurred.

I'll now address what I consider to be a serious error in the way Bill Clemens analyzes his data. The field of data analysis is one in which I have had a lot of experience--in contrast to my inexperience in paleontology--so I'll offer this criticism without apology. The "Tyrannosaurus rex femur" that appears at the 0.8 meter level is considered by Bill Clemens to mark the time at which the dinosaurs went extinct. I have "called him" on this point so many times in our little seminars, that I'm sure I'm not being unfair to him when I say that he really believes that the dinosaurs went extinct 3.4 meters before the iridium layer was deposited, or close to 30,000 years earlier. (And in a recent article,[29] he makes this point several times.) The various members of our group have come up with at least four different ways of demonstrating that the proper point to mark the disappearance of the dinosaurs--based on Bills' "highest observed fossil"--is measured in meters (rather than decimeters or decameters) above the "highest bone". (The fact that we proposed several new ways of

demonstrating that assertion, on several succeeding Tuesday meetings, is the best proof I can offer that we had not convinced Bill by our earlier arguments. Each week the proposer of the new explanation would say, ahead of time, "I'll bet this one will convince Bill Clemens").

The easiest way to show what the problem is, and why it is not important in the marine deposits, is to state it in its simplest form. We will assume that some fossils, for example, forams or dinosaurs, are seen in an exposed cliff face, with an average vertical spacing equal to L meters. (If we look at only half as wide a section of the face of the cliff, the appropriate value of L will of course be twice as large.) The hypothesis we are testing is that the creatures whose fossils we are observing were reproducing at a substantially constant rate, until they were suddenly eliminated, as the result of some catastrophic event. We have used four separate methods to show that the most probable location of the true "extinction layer" is exactly L meters above the highest observed fossil in that section. The four methods are 1) analytical, 2) by using computer-generated plots of randomly occurring "fossils," but with a known cut-off level not indicated on the plot, 3) the "Monte Carlo" random number method and 4) an analogy based on locating the U. S.-Canadian border by observing (a) the home of the most northerly U. S. citizen, and (b) the home of the northernmost U. S. Congressman. You may enjoy developing this analogy--it works quite well.

The second method corresponds most closely to what one finds in the field--a collection of fossils extending left and right, to the

edges of the page, but with no fossils in the upper part of the diagram, above some unmarked line, that was at a different height on each page. We passed out dozens of these plots, which were generated on the computer by Walter's student, Kevin Stewart, at one of our seminars, and asked each participant to guess where the computer had located the "sharp cut-off." (In some of these plots, the computer was instructed to weight the surviving fossil population differently in various lithological layers. We did this because Dale Russell's experience as a dinosaur fossil hunter has taught him that in some formations, such as sandstones, there is a larger chance of finding fossils than there is in siltstones or mudstones. So the computer-generated fossil plots corresponded as closely as we could make them to a real field situation.) When the "key" was revealed, it was clear that no one had done a good job in locating the Ir layer, but those of us who believed the analytical theorem--that one should pick a point that is above the highest fossil by an amount equal to the average spacing, L--did better than the paleontologists, who have been taught for most of their professional lives to take most seriously the levels corresponding to the "first appearance," and the "last appearance" of any species. The difference between those two levels is called the "range" of the species, and it is accepted that all species do (or will) become extinct at some level.

I believe the reason for the wider acceptance amongst paleontologists of the idea that the asteroid impact led to the extinction of the forams is that the average spacing L between their

fossils in limestone that crosses the C-T boundary can be a very small fraction of a millimeter. The boundary clay has a lower boundary that is definable to only somewhat less than a millimeter, so the coincidence between the iridium layer and the "highest foram" is "perfect," and so "everybody" believes in the causal relationship between the asteroid and the extinction.

In the case of the dinosaur fossils, the average spacing is unknown, but in Bill Clemens' table it is slightly more than a meter. If we took it to be exactly 1 meter, and independent of lithological factors, the analytical expression for the chance that the iridium layer appeared at least 3.4 meters above the highest fossil is $p = e^{-3.4} = 0.033$. On the other hand, if the average spacing were 2 meters or 0.5 meters, the probabilities that the iridium layer is where it is are $e^{-1.7}$ or $e^{-6.8}$, equal to 0.183 and 0.0011, respectively. We will soon see that all of these probabilities are larger than the exceedingly small probability that Bill Clemens is forced to accept, when he says that the dinosaurs became extinct, for some unspecified reason--unconnected with the asteroid impact he has accepted, about 30,000 years before that impact took place.

It is easy to calculate the probability that the dinosaurs, which had dominated the earth for nearly all of the Mesozoic era--from about 200 million years ago, would become extinct just 30,000 years before any arbitrarily chosen time marker, for example, the asteroid impact; that probability is the ratio of those two times, or 1.5×10^{-4}. As I just said, that is smaller than any of the probabilities we can

construct from the "gap" data, and it suffers further from its completely ad hoc nature--there is nothing in the history of the earth that can be connected with this extraordinarily coincidental "extinction". On the other hand, our preferred scenario is tied solidly to a well documented catstrophe that is the most severe event of which we have any record. I really can't conceal my amazement that some paleontologists prefer to think that the dinosaurs, that had survived all sorts of severe environmental changes and flourished for 140 million years, would suddenly, and for no specified reason, disappear from the face of the earth (to say nothing of the giant reptiles in the oceans and air) in a period measured in tens of thousands of years. I think that if I had spent most of my life studying these admirable and hardy creatures, I would have more respect for their tenacity, and would argue that they could survive almost any trauma except the worst one that has ever been recorded on the earth--the impact of the C-T asteroid.

Since I mentioned the Monte Carlo method of demonstrating that one needs to add L to the height of the highest fossil, to locate the most probable position of the the iridium layer, I'll now show you [figure 14] the results of 20 computer-generated dinosaur fossil sequences. Each set was constructed by a random number generator, which positioned 50 dinosaur fossils randomly in a stratigraphic height of 100 meters. So L is 2.0 meters in all 20 sections. The sharp cut-off at the top is always located at 0 meters and you can see where the highest fossil is located in each section. You also see that if you assume the cut-off is at the highest bone, you guess wrong, on the average, but just L meters. But if you add L meters

Computer-generated "highest dinosaur"

L = 2 meters, D = 50 dinosaurs/100 meters

(zero elevation corresponds to true extinction)

Sample	Z (meters)	Z + L meters
1	-3.201	-1.201
2	-3.063	-1.063
3	-0.521	+1.479
4	-0.396	+1.604
5	-0.097	+1.903
6	-5.408	-3.408
7	-2.930	-0.930
8	-0.649	+1.351
9	-3.747	-1.747
10	-1.097	+0.903
11	-0.109	+1.891
12	-0.244	+1.756
13	-1.501	+0.499
14	-0.680	+1.320
15	-1.896	+0.104
16	-4.330	-2.330
17	-2.903	-0.903
18	-3.681	-1.681
19	-4.112	-2.112
20	-1.665	+0.335
Averages	-2.112	-0.112

Fig. 14. "Monte Carlo" table of the highest fossil in 20 random sequences of 50 fossils, each having a density of 50 fossils/100 meters.

to the highest bone in each section, then your average estimate of the position of the cut-off--in the 20 cases--is just right.

I said earlier that I'd point out the trouble Bill Clemens would be in if the "gradual decline" of the dinosaurs turned out to be real--which I continue to doubt. The trouble comes from the fact that the value of L that one must add to the height of the "last observed dinosaur", to locate the "most probable height" of the extinction level, is not the average value of L observed in some collecting site, but the much larger value of L associated with the smaller (declined) population near the time that the "highest fossil" was laid down. Since the probabilities of observing "gaps" (larger than G) between the highest fossil and the iridium layer (assuming it caused the extinction) are equal to $e^{-G/L}$, we see that Bill doesn't have a statistically significant experimental gap to explain, if he really believes in his "decline hypothesis." (The larger L is compared to G, the closer $e^{-G/L}$ approaches unity.)

I'm really sorry to have spent so much time on something that the physicists in the audience will say is "obvious", but some of my friends in the field of paleontology find it difficult to accept, and in fact, have used that non-acceptance to "prove" that the asteroid impact was unrelated to the extinction of the dinosaurs. And as I said earlier, I am confident that the two events are related causally.

The two questions I've heard most frequently in the last three days are, "where did the asteroid hit?" and "how is the theory being

accepted these days?" The answer to the first is that we don't know. No crater of the correct size (100-150 km diameter) and age is known on the earth, with the possible exception of the Deccan Traps region on the Indian subcontinent. Fred Whipple's[30] interesting suggestion that the asteroid hit the mid-Atlantic ridge, between Greenland and Norway and led to the formation of Iceland is unfortunately wrong, because paleomagnetic evidence shows that there wasn't any such ridge at the end of the Cretaceous period--Greenland and Norway hadn't yet separated. We may never see the crater, because 20% of the earth's crust, 65 million years ago, has since been subducted below the continents. So there is a 20% chance that the crater has disappeared forever, but there is also a finite chance that it still exists on some part of the ocean floor that hasn't been mapped with sufficient resolution to show it. Many geologists have written to suggest possible impact sites, and each one has looked pretty exciting at first glance. But all of them have had to be discarded, for one reason or another.

I'll conclude my talk by addressing the question concerning the acceptance of the theory. Almost everyone now believes that a 10 kilometer diameter asteroid (or comet or meteorite) hit the earth 65 million years ago, and wiped out most of the life in the sea. When we first said that the extinctions were caused by an asteroid, we had no information on the detailed composition of the asteroid, and in fact, no one had ever had a chance to analyze an asteroid. But if we had been a little more adventurous, we would have made an eighth

prediction--that we would eventually prove that the asteroid had a composition essentially identical to that of the most common solar system debris we know--the carbonaceous chondritic meteorite. We always assumed it did have that composition, but it didn't occur to us that there would be a way to "prove" it. This was first done by R. Ganapathy who found the ratios of platinum group elements in the Danish boundary layer corresponded roughly to carbonaceous chondritic meteorites.[31] We then measured the Pt/Ir and Au/Ir ratios in Danish and Spanish boundary clays with high precision, and they agree almost perfectly with Type I carbonaceous chondrites, and don't look at all like crustal or mantle material from anywhere on the earth. The measured ratios also agree with two other kinds of chondritic meterorites, but not with iron meteorites.

While I was in the process of editing the stenographic transcription of my talk, to make it suitable for reproducing in print, I read an article by J. David Archibald and Bill Clemens, entitled "Late Cretaceous Extinctions."[29] Its latest reference shows it to be contemporaneous with my talk. Bill Clemens and I had earlier discussed all the points I made in my talk, and almost all those made in his new article, so it will be useful for the reader--trying to decide for himself which point of view to adopt--if I comment on a few places where we obviously disagree. I have added (to this printed version) no new points that I didn't touch on in my talk, except for a few items that are labeled: [Note added in proof].

It would make this printed version of my talk much too long if I addressed all the points in the article with which I disagree. So I'll concentrate my attention on the alternative theories that Dave and Bill take seriously enough to discuss in some detail. They mention explicitly only two such theories, and both can be quickly dismissed, since the first--the supernova theory--is not consistent with Carl Orth's limit on the plutonium 244 near a continental boundary; he finds less than 10^{-4} of the amount called for by the theory. And furthermore that theory has already been abandoned by its three chief proponents, Mal Ruderman in physics, Dale Russell in paleontology, and Wallace Tucker in astrophysics.

The second theory is Steve Gartner's "Artic Spillover Model." This was an acceptable theory when it was proposed, several years ago, but it is no longer so, since it offers no reasonable explanation for the iridium layer in the ocean sediments, and no possible explanation for the iridium layers seen on continental sites. I'm really quite puzzled to see that in 1982, two knowledgeable paleontologists would show such a lack of appreciation for the scientific method as to offer as their only two alternative theories to that of the asteroid, a couple of outmoded theories. One can't use the excuse that when they were proposed, neither could be falsified. The facts of the matter are that as of today, both of them are as dead as the phlogiston theory of chemistry, and I haven't heard a serious suggestion in place of the asteroid theory. (But of course that situation has no bearing on whether or not the asteroid theory is correct.)

On the last page of their article, they speak of several vaguely defined non-catastrophic theories, but then they apparently (and I believe correctly) dismiss such theories by saying, "Looking back, it seems unlikely that gradual processes could have caused the extinctions that occurred at the end of the Cretaceous." This evaluation seems to be in good accord with a statement that appears near the beginning of the article, "From today's perspective, the extinction of the dinosaurs some 65 million years ago appears to have occurred almost literally overnight."

After reading this article at least six or eight times, I came away with the feeling that they are emphasizing four main points. Firstly, it is terribly difficult to make meaningful measurements in field paleontology, that tell very much about what happened 65 million years ago. I agree completely with this point, and my admiration for the observations that my newfound friends have made is enormous. But as you can tell, that admiration does not extend to some of the conclusions they draw from those observations.

Their second point is that the dinosaurs disappeared about 3 meters (approximately 30,000 years) below the Cretaceous-Tertiary boundary. They state this conclusion, explicitly, on 4 out of the 8 pages of their article, and it is the point that comes through loudest and clearest. (And you can see that even after trying in four different ways to convince Bill that such a gap has no significance, we really "struck out.")

Their third point is expressed in this way in the article's final sentence, "At present, the admittedly limited, but growing store of data indicates that the biotic changes that occurred before, at, and following the Cretaceous-Tertiary transition were cumulative and gradual and not the result of a single catastrophic event." Again, this point is made on at least 4 out of the 8 pages.

Their fourth point is not stated explicitly, but it comes through quite clearly--they do not take seriously the idea that the asteroid impact (if it in fact really occurred, and they never say that they believe that) had anything to do with the extinction of the dinosaurs. There is not a single indication that they take seriously any of the many properties of the iridium layer that I've discussed in this talk, and which lead me to conclude that the asteroid did trigger the dinosaur extinction. (You can be sure that before I make such a sweeping statement, I've carefully read and reread what Dave and Bill said about the iridum layer, each of the 13 times they mentioned the word iridium.)

It seems to me that their article is in no way responsive to the wealth of data that I've presented in this talk, and with which Dave and Bill are intimately familiar. If George Mallory of Everest fame were still alive, I think he'd say, "Gentlemen, you should take the iridium layer seriously--it is there!"

And since Archibald, Clemens and Hickey all assert that the extinctions weren't synchronous--the land plant extinctions, and the land animal (e.g., dinosaur) extinctions--let me end the technical

part of my talk with arguments that I find overwhelmingly convincing as to their precise synchroneity.

The Orth graphs, plus the rarity of iridium layers show that the oceanic and land plant extinctions were synchronous to better than 5 cm, or appreciably less than one thousand years. There are no data presented by any of the three authors I just mentioned that attempt to challenge that conclusion. But they do challenge the simultaneity of the land floral and faunal extinctions, based on the 3 meter "gap" between the "highest dinosaur" and the pollen changes. I can't think of anything to add to the set of four arguments I've already given to show that the "gap" has no experimental significance.

In trying to decide whether we or our critics are correct in our deductions, I suggest you compare two models. The first is ours, which says the asteroid was responsible for the iridium layer seen by Orth in New Mexico, and for the ones that we and others see all over the earth, in oceanic sections, and that anyone, using a hand lens, can see was synchronous with the oceanic extinctions. Our model says these two were synchronous to within a few years, so one doesn't need to calculate a probability--the theory simply predicts what we see--simultaneity within the resolution of the observations.

But if we take the Archibald, Clemens and Hickey position--that the asteroid had nothing to do with the land floral extinctions, then the observed time coincidence of the two events is purely a matter of luck, which can be expressed as a probability. The numerator is the very generous 1000 years I've assigned, and the denominator should be

the average time between "spikes" such as this dip in the pollen density. Since I've not heard of other spikes of this nature, I'll use for this average time, what I think of as the "characteristic species time," or one million years. So the probability that the observed simultaneity is due to pure luck unrelated to an asteroid impact, is about 10^{-3}. In physics, we don't treat seriously theories with such low a priori probabilities. (But if you look closely at the writings of Archibald, Clemens and Hickey, you find that they don't really have a viable competing theory--one that explains some reasonable fraction of the observational data. I think it is correct to say that their theory is that our theory is wrong!)

The simultaneity of the C-T extinctions in the oceans and on the land can also be demonstrated by a completely different argument, that depends only on forams, dinosaurs and iridium. Let us look at what our group concluded after seeing iridium layers in Italy, Denmark and New Zealand and deducing that these layers resulted from an asteroid impact. With the exception of Walter, none of the members of our group knew anything about the extinctions of the land animals. But we were forced to say that there would be an iridium layer seen in continental sites, precisely at the C-T boundary, as defined by the paleontologists. And this prediction relates to dinosaur extinctions on all continents, so we should see iridium layers just above the highest dinosaurs in Western North America, Argentina, France, Spain and Mongolia. (We haven't yet looked at the foreign locations, but I'd like you to remember that we didn't pick the site to examine; that

was a random selection.) As I've said, three of us knew nothing about Montana dinosaurs or the lower Z coal layer. But if we had known what Dave and Bill now say about that layer, we would have predicted (number nine) that the iridium enhancement would be found in the lower Z coal layer. (Here is what they say about that layer: "This coal came to represent the Cretaceous-Tertiary boundary in Montana, because remains of dinosaurs had not been found above it." [Emphasis added].) Note that this sentence doesn't mention pollen or mammals. So with no knowledge whatsoever about dinosaurs, we predicted that there should be an iridium enhancement at the (unknown to us) C-T boundary, which Dave and Bill could have told us was in the Z coal layer, and when we looked there, there it was! [Figure 12, see page 44] (Actually, we first looked in the region of Bill Clemens' favored place, 3 meters below the Z coal layer, and found no "signal." We then worked our way, slowly up ten centimeters at a time, until we saw the enhancement I've just shown you.)

If you believe the asteroid theory, as we do, then there is nothing surprising about this--that's just where the iridium had to be. But if you again take the point of view of our paleontologist critics--that the asteroid impact had nothing to do with the dinosaur extinction--then you can calculate the probability that we were simply lucky in that prediction. In this case, the numerator is the thickness of the Z coal layer, or about 4 cm, which we can again approximate as less than 1000 years. The denominator is again undetermined but certainly in the range of millions of years. So my estimate of the probability

that we were "lucky," even though our theory was quite invalid, is about 10^{-3}. And in case you think I'm simply repeating an old argument, I'll remind you that the 5 centimeter numerator in the first probability came from a comparison of the two halves of the Orth graph [Figure 10, see page 29], whereas the nearly same value for the numerator in the second probability calculaton came from the measured thickness of the lower Z coal layer, and our discovery of the iridium enhancement at its base [Figure 12, see page 44]. So the two sets of measurements are quite independent, and the rules of statistics say that we should multiply the two probabilities, to get an obviously absurd chance of the two sets of observations being due to luck; $p = 10^{-6}$. It is also interesting that we didn't have to calculate the probability that the iridium layer was in coincidence with the extinction of the forams; that probability has for its numerator, a distance more like a millimeter, in several places that are widely distributed over the globe.

I hope these exercises will show you why, as an experimentalist, I am convinced that the three extinctions in question were simultaneous--the oceanic extinction, the land floral extinction, and the land faunal extinction.

And before I leave the matter of probabilities, let me remind you that a few minutes back, I calculated the probability that the dinosaurs, which appeared on earth about 200 million years ago, would suddenly become extinct within about 3 meters, or about 30,000 years of some arbitrarily chosen time marker. (We did the calculation on

the assumption that the time marker was the time of the asteroid impact. But if the asteroid had nothing to do with the dinosaur extinction, as our critics believe, then there is no reason to use the asteroid impact as the "arbitrary time marker"--it could in fact be any arbitrarily assigned time.) And as I showed earlier, the probability that this happened "by luck" was about 1.5×10^{-4}. When I wrote the first draft of this paper, I treated this probability as independent of the other two -- its numerator is 30,000 years, rather than 1000 years, and its denominator is 200 million years rather than 10^6 years. So I multiplied the three probabilities together, to yield an overall probability that all three observations happened by luck -- assuming that the asteroid impact had no relationship to either of the land extinctions. But that is probably "overkill", for two reasons: (1) I shouldn't use Bill Clemen's erroneous conclusion that the 30,000 year "gap" is significant, to cast further doubt on his gradualistic theory. And (2) the 4 cm limit of error between the Z coal and the iridium layer, and the 3 meter interval between the Z coal layer and the "highest dinosaur" are not completely independent; both involve the location of the Z coal layer. But I think that a factor of 10^6 "working against" the Archibald-Clemens theory is impressive enough.

I'll conclude this talk with a brief discussion of how a theory is "proved". We all know, of course, that theories can't be proved, they can only be disproved, as Newton's theory of gravitation was disproved by the observations that led to the acceptance of Einstein's theory of gravitation. So let me change my words and ask how theories come to

be accepted. Here the classic example is the Copernican heliocentric theory, that displaced the Ptolemaic geocentric theory. It became accepted, not because Galileo saw the phases of Venus, as most of us believe, but simply because the heliocentric theory easily passed a long series of tests to which it was subjected, whereas to pass those same tests, the geocentric theories had to become more and more contrived. (That is why I've spent so much time telling you of the many tests and predictions that the asteroid theory has "passed.")

And finally, if you feel that I've been too hard on my paleontologist friends, and given the impression that physicists always wear white hats, let me remind you of a time when our greatest physicist, Lord Kelvin, wore a black hat, and seriously impeded progress in the earth sciences. We all know that he declared, with no ifs, ands or buts, that the geological time scale was all wrong; he was absolutely sure that the sun couldn't have been shining for more than about 30 million years, using the energy of gravitational collapse.

But most of us don't know that the first man to suggest the answer to this serious problem was Thomas C. Chamberlin,[32] a geologist at my Alma Mater--the University of Chicago. He said that since the sun had <u>obviously</u> been shining for a much longer time, there must be an as yet undiscovered source of energy in the <u>atoms</u> that make up the sun! And on this occasion, when the tables were turned, the physicists, who had been dragging their heels for a long time, eventually discovered

"atomic energy" for themselves, (and even convinced everyone that it was "their baby"), and then went on to explain in detail just where the sun's energy comes from.

Every science has much to learn from its sister sciences, and I look forward to the continuation of our cross-disciplinary Tuesday morning sessions.

Thank you.

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