"Physicists would no doubt cast a jaundiced eye upon the newest theories of quantum physics published by biologists. Yet expert opinion about the demise of the dinosaurs is apparently off-limits to no one."

J. David Archibald
Dinosaur Extinction and the End of an Era: What the Fossils Say, p. 12

"In part, the fervent new efforts of paleontologists to unravel the puzzle of mass extinction have resulted from our chauvinistic impulse to convince the world that astronomers do not have simple answers to complex geological problems."

Steven M. Stanley
Extinction, p. x

"You cannot study why the dinosaurs died by studying dinosaurs. It's just crazy. It's insane. ... There are three hundred [and] eleven skeletal fragments of dinosaurs, worldwide, for the last nine million years of Cretaceous time... I have zero patience for guys who are going to prove that dinosaurs are dying out slowly by counting dinosaur skeletons."

Dale A. Russell
qtd. in Psihoyos and Knoebber, *Hunting Dinosaurs*, p. 258

"I think our [i.e., vertebrate paleontologists'] major contribution has been to tenaciously resist the innate reductionism of physical scientists and to keep posing pertinent paleobiological questions."

William A. Clemens
Response to VRTPALEO Listserver Survey, January 2, 2003

University of Alberta

'Off-Limits to No One'?:
Vertebrate Paleontologists and the
Cretaceous-Tertiary Mass Extinction

by

Keynyn Alexandra Ripley Brysse ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Arts

in

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Abstract

On June 6, 1980, an article entitled "Extraterrestrial cause for the Cretaceous-Tertiary extinction: experimental results and theoretical interpretation" was published in *Science*. Its authors, physicist Luis Alvarez, his son, geologist Walter Alvarez, and nuclear chemists Frank Asaro and Helen Michel, presented evidence that an asteroid or comet had hit the Earth 65 million years ago, and argued that it caused the mass extinction known to have occurred at that time. Scientists of many fields embraced the Alvarez impact hypothesis. However, the majority of vertebrate paleontologists, while accepting that an impact had taken place, rejected the impact as the (sole) extinction cause. Vertebrate paleontologists summoned several theoretical, social, and scientific objections to the Alvarez theory, its theoretical presuppositions, its defenders, and their manner of defense. It is crucial to examine what vertebrate paleontologists have said during the course of this debate precisely because – until now – their objections have gone largely unheard.

Acknowledgments

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I would like to thank Sandra Johnson and the rest of the staff at the Niels Bohr Library in the American Institute for the History of Physics, for their generous loan of several of Dr. William Glen's interview tapes from his *Project in the History of the Mass-Extinction Debates: Oral History Interviews, 1984-1994.* I also thank Dr. Glen for his kind permission to use information from these interviews, and Dr. Robert Smith for bringing these interviews to my attention in the first place. I extend special thanks to those members of the vertebrate paleontology community who responded to the survey I posted on the VRTPALEO Listserver owned by Dr. Sam McLeod of the University of Southern California. I am particularly grateful to Tim Tokaryk for sending me a copy of his bibliography of the K-T impact debate, which proved to be indispensable.

I would like to thank Dr. Lesley Cormack for going above and beyond the duties of a supervisor. Whenever I needed help – with anything from correcting a paper to writing a letter to just letting off steam – she was there for me. Without her support, feedback, guidance, and friendship, this thesis would never have been finished.

Finally, I would like to take this opportunity to recognize Dr. Andrew Ede, who is one of the best teachers I know. It was his skillful, entertaining, and utterly fascinating lectures on history of science which helped me to finally figure out what I want to be when I grow up.

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List of Nomenclature and Abbreviations

bolide	An asteroid or comet.
EQ	Encephalization quotient; obtained by calculating an organism's brain weight to body weight ratio.
K	The accepted scientific abbreviation for the Cretaceous period, the last period in the Mesozoic era, roughly 145-65 million years ago. K is short for 'Kreide', the German word for chalk, which recognizes the extensive chalk beds for which the Cretaceous was named. (The letter C is already in use as the symbol for the Carboniferous period.)
T	The accepted scientific abbreviation for the Tertiary period of geological time, the first period in the Cenozoic era, approximately 65-2 million years ago. T is short for 'Tertiary'.
K-T, K/T, KT, KTB, C-T	These are all various ways of designating the boundary between the Cretaceous and Tertiary periods, a time marked by the second-largest mass extinction known. The most correct abbreviation is the first, because the use of a hyphen separates the two periods without implying the (incorrect) superposition of the Cretaceous period on top of the Tertiary period, as does the slash. A few authors, including the Alvarez team in many of their papers, have used C-T, which is incorrect. Except where a different abbreviation is used in a direct quotation, I will use "K-T" and "K-T boundary" to refer to this moment in geological time.
K-T transition	A few authors, including vertebrate paleontologist William A. Clemens, use "K-T transition" instead of "K-T boundary" to emphasize their belief that the mass extinction was gradual, not sudden. I use 'boundary' because it is the term used by the majority of paleontologists and other participants in the impact debate.
Maastrichtian or Maestrichtian	The last stage or age (smaller time unit) in the Cretaceous period.
Paleocene	The first epoch (smaller time unit) in the Tertiary period.
Paleogene	Some authors use two shorter periods, the Paleogene (abbreviated Pg) and Neogene, instead of the longer Tertiary period. These authors refer to the K-T boundary as the K-Pg boundary.
Phanerozoic	The Phanerozoic eon is that period of time, from approximately 570 million years ago to the present, from which fossils can be found. It is now thought that life on Earth originated long before Phanerozoic time, but the entire history of complex multicellular life on Earth is encapsulated within the Phanerozoic eon.
Pu-244	A radioactive isotope of plutonium; read as "plutonium 244".
SVP	The Society for Vertebrate Paleontology. This association of vertebrate paleontologists publishes the *Journal of Vertebrate Paleontology*. There is a link to the VRTPALEO Listserver on the SVP's website, but the Listserver is operated independently.

Introduction

In the June 6, 1980 issue of *Science*, a popular multi-disciplinary science magazine put out under the auspices of the American Association for the Advancement of Science (AAAS), four scientists from the University of California at Berkeley published an article in which they presented evidence for the impact of a comet or asteroid on the Earth at the end of the Cretaceous period, approximately 65 million years ago. They suggested that the impact was the cause of the mass extinction already known to have occurred at that time.[1] This paper, entitled "Extraterrestrial cause for the Cretaceous-Tertiary extinction: experimental results and theoretical interpretation," spawned a debate encompassing thousands of publications by hundreds of scientists from a multitude of scientific disciplines, which has been described as "perhaps the most popular scientific controversy of the late twentieth century."[2]

Speculation regarding the cause of any mass extinction might belong most appropriately to the field of paleontology, which explores the history of life on Earth using the evidence of the fossil record. In the particular case of the Cretaceous-Tertiary mass extinction, during which the dinosaurs[3] and many other vertebrate groups met their demise, one would expect vertebrate paleontologists to be at the forefront of extinction research. In fact, only a small number of vertebrate paleontologists participated in the debate that followed the proposal of the Alvarez theory. Of those vertebrate paleontologists who participated in the debate or commented on the Alvarez hypothesis and its ramifications, the vast majority rejected the impact hypothesis in favor of a more gradual and terrestrial explanation for the mass extinction. While this rejection was noted by other participants in and commentators on the impact debate, the reasons behind it were seldom articulated or explored, and in many cases the evidence and arguments

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[1] Luis W. Alvarez, Walter Alvarez, Frank Asaro, and Helen V. Michel, "Extraterrestrial cause for the Cretaceous-Tertiary extinction: experimental results and theoretical interpretation," *Science* vol. 208, no. 4448 (June 6, 1980): 1095-1108.

[2] Norman MacLeod and Gerta Keller, "Introduction", in Norman MacLeod and Gerta Keller, eds., *Cretaceous-Tertiary Mass Extinctions: Biotic and Environmental Changes* (New York and London: W. W. Norton & Company, 1996), 5.

[3] Because modern taxonomy places the birds within the dinosaurs, they are technically not extinct, since their descendants, the birds, are still with us. For the sake of simplicity, however, I will use the term

presented by vertebrate paleontologists against the impact theory (or in favor of a rival theory) were dismissed, discredited, or outright ignored. This thesis explores the rejection of the Alvarez hypothesis by the vertebrate paleontology community, a facet of the impact/mass extinction debate which has gone largely ignored by other researchers and indeed, by most participants in the debate. Several authors, including reporters and debaters, have stated that this debate is over, and indeed that it was settled several years ago.[4] I argue that the debate is not closed, because the voices of vertebrate paleontologists, who regard the evidence of their field as the final arbiter of the debate, have not been heard. It is necessary to explore the role of vertebrate paleontologists within the impact debate in order to discover the debate's true complexities, and to interpret all of its ramifications.

Through the history of life on Earth, there have been several episodes of mass extinction, or events in which great numbers of species have disappeared, eventually to be replaced by entirely new kinds of creatures. One of the largest of these mass extinctions occurred 65 million years ago, and it is used as the marker to divide the Cretaceous Period, the last period in the Mesozoic era (informally known as the age of dinosaurs and other reptiles), from the Tertiary Period, the first period in the Cenozoic era, which marks the beginning of the age of mammals (Figure 1). Approximately

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"dinosaurs" to designate the informal group "non-avian dinosaurs", which did all become extinct by or at the end of the Cretaceous period.

[4] Walter Alvarez and Frank Asaro, "What caused the mass extinction? An extraterrestrial impact," *Scientific American* vol. 263, no. 4 (October 1990): 78-84. Alvarez and Asaro stated: "We now believe that we have solved the mystery" (p. 78), and "Evidence that a giant impact was responsible for the extinctions at the end of the Cretaceous has finally rendered the catastrophic viewpoint respectable" (p. 84).
Steven D'Hondt, "Theories of terrestrial mass extinction by extraterrestrial objects," *Earth Sciences History* vol. 17, no. 2 (1998), 167. D'Hondt wrote: "[T]he impact of a large asteroid or comet is now widely accepted as the likely cause of the end-Cretaceous mass extinction."
Beverly Halstead, "The revenge of the soft scientists," *The Scientist* vol. 1, no. 3 (December 15, 1986): 12. Halstead wrote: "[T]he notion that the dinosaurs were wiped out as the consequence of an asteroid's splatting the planet... was an eye-catching idea that gripped everyone's imagination and it took hold so firmly that many people, scientists among them, speak of this event now as an established fact."
Roger Lewin, "Extinctions and the history of life," *Science* vol. 221, no. 4614 (September 2, 1983), 935. Lewin wrote: "[F]or many at least, asteroid impact has been accepted as a causative agent in mass extinction."
Antony Milne, "Book review: *Charles Frankel, The End of the Dinosaurs: Chicxulub Crater and Mass Extinctions* (Cambridge: Cambridge University Press, 1999)," *Isis* vol. 93, no. 4 (December 2000): 678-679. See Conclusion for a discussion of Milne's review.

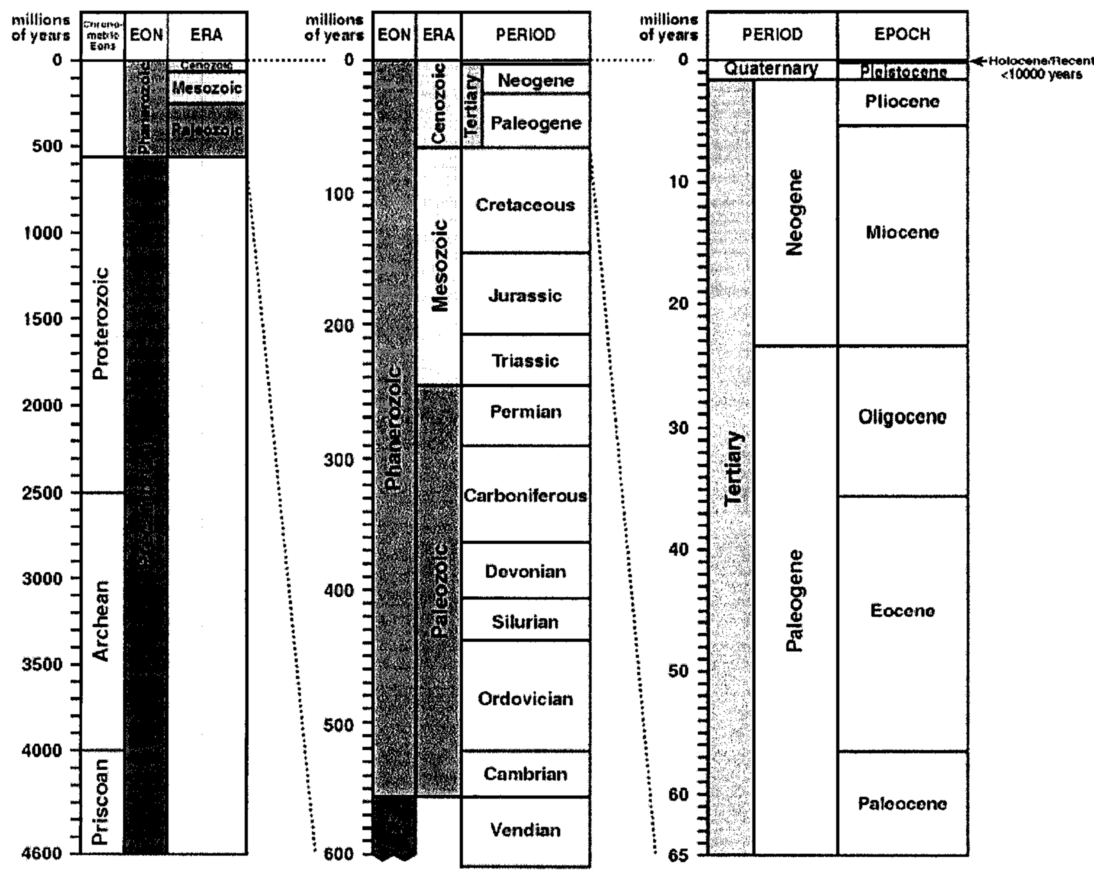

Figure 1. The Geological Time Scale

The Phanerozoic eon, which includes the entire history of multicellular life on Earth, comprises only the last 500 million years of the Earth's 4.6-billion year history. The Phanerozoic eon is divided into three eras, the Paleozoic, Mesozoic, and Cenozoic. The boundary between the Mesozoic and Cenozoic eras, approximately 65 million years ago, is also the boundary between the Cretaceous period (the last period in the Mesozoic era, abbreviated K) and the Tertiary period (the first period in the Cenozoic era, abbreviated T).

The last stage or age within the Cretaceous Period is known as the Maastrichtian (also spelled Maestrichtian). Some scientists divide the Tertiary period into two smaller units, the Paleogene and the Neogene; and within the Tertiary or Paleogene period, several epochs are recognized, the oldest of which is the Paleocene epoch. Some scientists use these other unit names to refer to the boundary 65 million years ago (e.g., the K-Pg or Cretaceous-Paleogene boundary), but it is most commonly known as the K-T boundary.

Source: © 1996 Andrew MacRae, Department of Geology and Geophysicis, University of Calgary <http://www.geo.ucalgary.ca/~macrae/timescale/time_scale.gif> (original in colour) seventy percent[5] of all species then in existence were wiped out at or by the K-T boundary, as it is called. The most famous group to be extirpated at this time was of course the dinosaurs, but all life on land, in freshwater systems, and in the oceans was affected in various degrees, from plants and mammals to marine reptiles and molluscs, down to microscopic marine organisms.

Paleontologists, other scientists, and many non-scientists have wondered for many years what caused the K-T mass extinction. It has been a very complicated question, with no immediately obvious solution. A major problem was that not all species appeared to have become extinct at the same time, or at the same rate. Many microscopic marine organisms, for example, flourished right up to the end of the Cretaceous, and then seem to have vanished abruptly right at the boundary. Dinosaurs, on the other hand, may have declined steadily over the last few million years of the Cretaceous, and, according to some experts, may have died out well below the K-T boundary. A few scientists have even questioned whether there was a mass extinction at all at this time: if the extinctions occurred over a period of several million years, can they really be described as one event?

Prior to 1980, there was nothing remotely resembling a consensus among scientists regarding the cause of the K-T extinction, and most paleontologists felt that we might never know what really happened. Although literally hundreds of extinction causes had been proposed, some silly and some serious[6], none were subject to practical

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[5] The number of species thought to have gone extinct at this time is a matter of debate. Most scientists usually give a figure of 70-75% species extinction. See for example:
Kenneth J. Hsu, *The Great Dying* (San Diego: Harcourt Brace Jovanovich, 1986), 54. Hsu estimated 75% species extinction.
John C. Briggs, "Mass extinctions: fact or fallacy?" 230-236, in William Glen, ed., *The Mass-Extinction Debates: How Science Works in a Crisis* (Stanford: Stanford University Press, 1994), 235. Briggs noted that K-T extinction estimates usually fall between 50% and 80% of species.
J. David Archibald, "I. Extinction, Cretaceous," 221-230, in Philip J. Currie and Kevin Padian, eds., *Encyclopedia of Dinosaurs* (San Diego: Academic Press, 1997), 222. Archibald stated that most authors claim a species-level extinction rate of 75%, but cautioned that "there are no studies documenting this level of extinctions for species". He also stated that in the Western Interior of North America, the extinction of vertebrate species at the K-T boundary appears to be approximately 50%.
Although some recent estimates of species level extinction have been more conservative (see for example Robert E. Sloan, J. Keith Rigby, Leigh M. Van Valen, and Diane L.Gabriel, "Gradual dinosaur extinction and simultaneous ungulate radiation in the Hell Creek Formation," *Science* vol. 232, no. 4750 (May 2, 1986): 629-633, discussed in Chapters 3 and 4), the vast majority of paleontologists agree that there was a mass extinction of at least 50% of species at or by the end of the Cretaceous period, and that this mass extinction was a significant departure from the level of background extinction.
[6] Michael J. Benton, "Scientific methodologies in collision: the history of the study of the extinction of the dinosaurs," *Evolutionary Biology* vol. 24 (1990), 381-385. Benton distinguished three phases of interest in

scientific testing, and the question of dinosaur extinction, and indeed, extinction in general, had been demoted to the status of armchair speculation. Most vertebrate paleontologists came to regard the extinction question as almost unscientific, as so many non-paleontologists kept proposing untestable and often ludicrous dinosaur extinction theories.[7] Accredited paleontologists and geologists noted that there had been an extensive regression of the world's oceans at the end of the Cretaceous period, as well as an episode of intense volcanism and a change in the Earth's climate.[8] Some respectable extinction theories were proposed invoking these terrestrial mechanisms as causes, but in general, it became simpler and safer to merely ignore the extinction question altogether.[9] Dinosaur paleontology itself was also just coming back into the light after a long period of disinterest. By the 1930s, many scientists felt there was nothing new to learn about dinosaurs, and they remained a relatively quiet topic until the hot-blooded/cold-blooded debate of the 1970s caused a renewed interest in these extinct reptiles.[10]

The Alvarez hypothesis, widely regarded as the first testable theory of dinosaur (and other) extinction[11], brought the extinction question back into the realm of respectable scientific inquiry. The Alvarez team consisted of Nobel prize-winning particle physicist Luis Alvarez, his son Walter Alvarez, a geologist/geophysicist, and nuclear chemists Frank Asaro and Helen Michel. Scientists, media, and the public alike were all immediately captivated by the Alvarez impact hypothesis, as it came to be called; but the paleontological community was stunned. Had the greatest mystery in the history of paleontology really been solved, and could it really have been solved by a group of non-paleontologists?

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the study of dinosaur extinction: "(1) the non-question phase (up to 1920); (2) the dilettante phase (1920-1970); (3) the professional phase (1970 onward)" (p. 371), and provided a comprehensive list of all hypotheses of dinosaur extinction cause ever proposed, whether serious or tongue-in-cheek (p. 381-385).

[7] *Ibid.*, 385.

[8] Cameron J. Tsujita, "The significance of multiple causes and coincidence in the geological record: from clam clusters to Cretaceous catastrophe," *Canadian Journal of Earth Sciences* vol. 38 (2001), 279-281.

[9] Benton, "Scientific methodologies in collision," 385.

[10] Erik Stokstad, "Popular interest fuels a dinosaur research boom," *Science* vol. 282, no. 5392 (November 13, 1998), 256. See also David Spalding, *Into the Dinosaurs' Graveyard: Canadian Digs and Discoveries* (Toronto: Doubleday Canada, 1999), 95, 114.

[11] See for example: Elisabeth S. Clemens, "Of asteroids and dinosaurs: the role of the press in the shaping of scientific debate," *Social Studies of Science* vol. 16, no. 3 (August 1986), 428-430.
Peter D. Ward, *The End of Evolution: On Mass Extinctions and the Preservation of Biodiversity* (New York: Bantam Books, 1994), 138.

In their paper, the Alvarez team described how they had found an unusually high concentration of the element iridium in a layer of clay deposited right at the K-T boundary. They had found this iridium anomaly in boundary clays from Italy, Denmark, and New Zealand, indicating that it had a worldwide distribution. Iridium, a member of the platinum group of elements, is extremely rare on the surface of the Earth, but occurs in much greater quantities elsewhere in the universe. The Alvarez team thought at first that the iridium might have come from a supernova, but when they failed to find a particular isotope of plutonium characteristic of supernova explosions, this theory was ruled out. Further analysis of the isotopes of iridium present suggested that it had come from somewhere much closer at hand, in our own solar system. The Alvarez team eventually reached the startling conclusion that an asteroid or comet (collectively called bolides) approximately ten kilometres in diameter struck the Earth at the end of the Cretaceous period, releasing tons of iridium and other material into the atmosphere, where it spread around the world and eventually formed the iridium-enriched boundary clay that Walter Alvarez would discover in Italy sixty-five million years later.

Since there were no paleontologists, biologists, zoologists, or other life scientists on the Alvarez team, it might have been prudent of them to end their article here, with the evidence for an extraterrestrial impact at the K-T boundary, and leave the biological implications for the experts to figure out. However, they went on to make the bold assertion that the bolide impact was the sole cause of the K-T mass extinction. While the iridium they initially detected is itself harmless, the impact that it pointed to would certainly have wreaked havoc on the Earth – although the magnitude of this devastation, and its specific effects on living organisms, were hotly contested. The Alvarez team hypothesized that the impact sent up a worldwide dust cloud that halted photosynthesis for several years, collapsing marine and terrestrial food chains and leading to the observed annihilation of 75% of the Earth's species. The Alvarez team were confident, as they indicated in their paper, that the impact and its aftermath, particularly the ensuing dust cloud, were sufficient to explain all of the end-Cretaceous extinctions.[12]

MacLeod and Keller, "Introduction," 2.

[12] Luis Alvarez et al, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," 1095-1108. The authors briefly discuss some published work on the K-T extinctions, not all of which appear to have

The postulated effects of the impact underwent substantial revision over the next several years, by the original Alvarez team and by other researchers. For example, it was soon realized that the dust would actually settle out of the atmosphere in several months, not several years. Other effects of impact were also proposed, including global forest fires, acid rain, global warming, 'impact winter', and changes in ocean chemistry. A search was also undertaken for the so-called smoking gun: the impact crater. Eventually, depending on which source one consults, up to thirteen craters of approximately K-T boundary age have been found.[13] The largest of these, and the one widely regarded as "the" crater, is a 180- to 300-kilometre structure on the Yucatan peninsula.[14] It is called Chicxulub after a town at its center, and although it was first identified in 1980 or thereabouts, proponents of the impact hypothesis did not become aware of it until ten years later.[15]

The Alvarez impact/extinction hypothesis was the first testable theory of (dinosaur) extinction, and the response among scientists, the press, and the public was immediate and overwhelming. Virgil L. Sharpton and Peter D. Ward, in the preface to their volume based on the second Snowbird conference on the impact debate, wrote:

> The wealth of multidisciplinary research that has resulted from testing and extending the 'Alvarez hypothesis' is staggering, and perhaps more than any other scientific debate during this decade [the 1980s], has shaped the course of human activity.[16]

William Glen, a geologist turned historian of science who has made this debate the focus of his research for the past twenty years, wrote in 1990:

> It is hard to overstate the impact of the impact hypothesis. In the past decade more than 2,000 papers and books have touched on various aspects of the controversy, and the flood of publications shows no sign of abating.

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occurred simultaneously, but concluded that they expect the extinctions will eventually be shown to have occurred simultaneously (p. 1107). They also stated that their hypothesis "accounts for the [Cretaceous-Tertiary] extinctions" (p. 1095).

[13] David Brez Carlisle, *Dinosaurs, Diamonds, and Things from Outer Space: The Great Extinction* (Stanford: Stanford University Press, 1995), 169.

[14] Richard A. Kerr, "Huge impact tied to mass extinction," *Science* vol. 257, no. 5101 (August 14, 1992): 878-880.

[15] Ward, *The End of Evolution*, 144-145.

[16] Virgil L. Sharpton and Peter D. Ward, "Preface," in Virgil L. Sharpton and Peter D. Ward, eds. *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality, Geological Society of America Special Paper 247*, (Boulder: The Geological Society of America, Inc., 1990), x.

> Careers have been redirected, long-quiescent areas of research have been rejuvenated, and workers in formerly isolated fields have been swept into collaborative efforts.[17]

These 'formerly isolated fields' include physics, chemistry, oceanography, geology and virtually all of its subdisciplines, and vertebrate and invertebrate paleontology. Several workers have recognized the uniqueness of the impact debate in fostering communication and collaborative research efforts between scientists from what are usually autonomous disciplines. For example, geologist James Powell made the following statement:

> One of the most beneficial by-products of the Alvarez theory is the way in which it has brought together scientists from an unprecedented variety of disciplines. Advances have been made that would have been impossible had only one group been involved. In this sense, few theories in the history of science have been as fertile as the Alvarez theory.[18]

It has been widely recognized that the Alvarez impact hypothesis and its corollaries have sweeping, even revolutionary, implications for the study of the natural sciences. For example, Powell wrote:

> If... impact did cause the [Cretaceous-Tertiary mass] extinction, then paleontology, geology, and biology would never be the same. Our conception of the role of chance in the cosmos, our view of life and its evolution, our understanding of our own place – each would be irrevocably altered.[19]

Graham Ryder, David Fastovsky, and Stefan Gartner agreed, in the preface to their volume based on the third Snowbird conference on the impact debate: "The ramifications and philosophical implications are much wider than just the Cretaceous-Tertiary boundary itself, extending to the history of life on Earth in general."[20]

In their landmark paper, as well as in subsequent publications, the Alvarez team have presented as one theory two independent ideas: first, that an asteroid or comet had impacted with the Earth at the end of the Cretaceous period, and second, that it was the

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[17] William Glen, "What killed the dinosaurs?" *American Scientist* vol. 78, no.4 (July-August 1990), 354.
[18] James Lawrence Powell, *Night Comes to the Cretaceous: Dinosaur Extinction and the Transformation of Modern Geology* (New York: W. H. Freeman and Company, 1988), 149.
[19] *Ibid.*, 126.
[20] Graham Ryder, David E. Fastovsky, and Stefan Gartner, "Preface", in Graham Ryder, David E. Fastovsky, and Stefan Gartner, eds., *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History, Geological Society of America Special Paper 307* (Boulder: The Geological Society of America, Inc., 1996), vii.

agent responsible for the end-Cretaceous mass extinction.[21] These two ideas have since been recognized – by paleontologists and some other scientists, if not always by impact supporters and the press – as independent hypotheses which must be proved (or disproved) individually.[22] In many cases, the second part of the Alvarez hypothesis – the idea that the impact caused the mass extinction – is asserted rather than proved, and those scientists best placed to prove (or disprove) this assertion – vertebrate paleontologists – are never brought in to be heard. The struggle to separate and test these two hypotheses, and in particular the ambiguity of the evidence surrounding the cause(s) of the K-T mass extinction, has formed the basis of the impact/mass extinction debate.

Many authors, both participants in the debate and commentators on it, have suggested that the popularity of the Alvarez hypothesis with scientists of all disciplines, the public, and the press derives in large measure from its alleged connection to the extinction of the dinosaurs.[23] Luis Alvarez himself has stated that his interest in the K-T

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[21] Luis Alvarez et al, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," 1095. The very title of the paper causally links the bolide impact with the mass extinction. Also, in the summary (p. 1095), the authors wrote "*A* hypothesis is suggested which accounts for the extinctions *and* the iridium observations." (Emphasis added.)
Also see Luis W. Alvarez, *Alvarez: Adventures of a Physicist* (New York: Basic Books, Inc., Publishers, 1987), 251, 256-257. Alvarez referred repeatedly to "our impact theory of (mass) extinctions" (p. 251 and 256). Also, while describing the genesis of the impact/extinction hypothesis, Alvarez noted "It wasn't at all obvious what brought in the pulse of iridium *and* killed most of the creatures on earth." (p. 256, emphasis added.)

[22] William Glen, "A manifold current upheaval in science," *Earth Sciences History* vol. 17, no. 2 (1998): 195. Glen wrote: "[I]nterviewees and journalists generally referred to the hypothesis as a single unified idea, without making the impact phenomenon discrete from its role as mass-extinction cause."
William A. Clemens, J. David Archibald, and Leo J. Hickey, "Out with a whimper not a bang," *Paleobiology* vol. 7, no. 3 (1981): 293. These authors cautioned that the Alvarez hypothesis "must be recognized as a composite of two assertions that have to be clearly decoupled."

[23] Elisabeth S. Clemens, "The impact hypothesis and popular science: conditions and consequences of interdisciplinary debate," in William Glen, ed., *The Mass-Extinction Debates: How Science Works in a Crisis* (Stanford: Stanford University Press, 1994), 93.
William A. S. Sarjeant and Philip J. Currie, "The 'Great Extinction' that never happened: the demise of the dinosaurs considered," *Canadian Journal of Earth Sciences* vol. 38 (2001): 239.
Niles Eldredge, "Foreword," ix-xiv, in MacLeod and Keller, eds., *Cretaceous-Tertiary Mass Extinctions: Biotic and Environmental Changes*, x.
An Australian journalist made the following comment following the proposal of the Raup-Sepkoski periodic extinction hypothesis: (Ian Warden, *The Canberra Times* (May 20, 1984), qtd. in Elisabeth Clemens, "The impact hypothesis and popular science," p. 437): "To connect the dinosaurs, creatures of interest to everyone but the veriest dullard, with a spectacular extraterrestrial event like the deluge of meteors… seems a little like one of those plots that a clever publisher might concoct to guarantee enormous sales. All the Alvarez –Raup theories lack is some sex and the involvement of the Royal family and the whole world would be paying attention to them."

event arose from a desire "to shed some light on what was really one of the greatest mysteries in science – the sudden extinction of the dinosaurs."[24] This connection therefore implies a vested interest among impact supporters in maintaining the link between impact and extinction. Powell phrased it thus: "[I]f the collision that left the Chicxulub crater behind did *not* cause the extinction of the 70 percent of species that perished at the end of the Cretaceous, the Alvarez theory would remain merely a scientific curiosity."[25]

One factor in this debate which has been a source of frustration to vertebrate paleontologists is the large number of scientist and media participants who explicitly refer to the asteroid impact as the (sole) cause of dinosaur extinction (or of the mass extinction in general) without providing any scientific evidence, or often, any discussion at all, of their reasons for doing so. As vertebrate paleontologist J. David Archibald points out, although a large number of the books and articles published on the impact controversy specifically connect dinosaur extinction to the asteroid hypothesis, very few of them substantiate this claim with an examination of the dinosaur fossil record – even when dinosaur extinction is mentioned in the title of the book or paper.[26] Luis Alvarez freely admitted to making this assumption in his own work: "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."[27]

In fact, despite the almost universal popular connection between the impact hypothesis and the extinction of the dinosaurs, those scientists who do examine the dinosaur fossil record, and vertebrate paleontologists in general, have been the most vocal opponents of the hypothesis of mass extinction by extraterrestrial impact. The almost

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Michael E. Williams, "Catastrophic versus noncatastrophic extinction of the dinosaurs: testing, falsifiability, and the burden of proof," *Journal of Paleontology* vol. 68, no. 2 (1994): 183.

[24]Luis W. Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," *Proceedings of the National Academy of Science* vol. 80 (January 1983), 632.

[25] Powell, *Night Comes to the Cretaceous*, 126.

[26] J. David Archibald, *Dinosaur Extinction and the End of an Era: What the Fossils Say* (New York: Columbia University Press, 1996), xvii.

[27]Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 637. Many paleontologists would argue that there is still no direct connection between the two.

universally negative reaction among vertebrate paleontologists to the Alvarez hypothesis has been documented – although largely unexplored – from the beginning of the debate.

Vertebrate paleontologist Robert L. Carroll, in his 1988 textbook *Vertebrate Paleontology and Evolution*, credited the Alvarez hypothesis with creating "an enormous interest in the problem of extinction at the end of the Mesozoic," but also stated that "Physical scientists tend to accept the major conclusions reached by Alvarez but contest some details. Scientists who have studied the fossil record have generally been highly critical."[28] William Glen noted that: "Vertebrate paleontologists, in greater proportion than specialists of any other subdiscipline within or beyond paleontology, objected to the impact hypothesis (both the impact and impact-as-extinction-cause postulates)."[29] Richard Kerr, who has editorialized the impact debate in *Science* since its inception, wrote in 1988 that "From the beginning, the large impact explanation of the mass extinction 66 million years ago was just too much for paleontologists to swallow."[30]

Although scientists among these fields exhibited varying levels of support or skepticism towards the Alvarez hypothesis, no other discipline as a whole reacted as negatively as the vertebrate paleontology community. At the same time, although this negative reaction was well documented in opinion polls, interviews, and the comments made by impact proponents about vertebrate paleontologists, vertebrate paleontologists as a community remained primarily silent on the impact/mass extinction issue. As we shall see in later chapters, relatively few of the thousands of publications on the subject of the impact debate were authored or co-authored by vertebrate paleontologists. A select few members of the community did research and publish on matters relevant to the impact/mass extinction debate, but in general the vertebrate paleontological community seemed largely to ignore and to be ignored by the controversy that was raging all around them. The reasons behind their silence will be explored in this thesis.

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[28] Robert L. Carroll, *Vertebrate Paleontology and Evolution* (New York: W. H. Freeman and Company, 1988), 327.

[29] William Glen, "Observations on the mass-extinction debates," 39-54, in Ryder, Fastovsky, and Gartner, eds., *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History*, 46.

[30] Richard A. Kerr, "Snowbird II: clues to Earth's impact history," *Science* vol. 242, no. 4884 (December 9, 1988), 1380. The fact that Kerr gives the time of the K-T mass extinction as 66 million years ago is not particularly significant. There is a certain amount of uncertainty in any geological date, and the K-T boundary is typically placed within a range from 64 to 66 million years ago.

Several authors, including Michael J. Benton, David M. Raup, Karl W. Flessa, and William Glen, have discussed the objections raised by scientists of various disciplines to the Alvarez hypothesis, although none has focused on vertebrate paleontologists in particular. In his various book chapters and articles, Glen has tended to divide impact debate participants into 'impactors', or those who supported the idea that an impact caused the K-T extinction, and 'volcanists', or those who believed the extinction was caused by a massive episode of flood basalt volcanism. Glen did recognize that there are some scientists, like most vertebrate paleontologists, who did not belong to either camp, and who might have acknowledged that an impact took place but did not regard it as the cause of the mass extinction. Glen's work only mentions this third camp briefly, however, and focuses instead on the various scientific arguments marshaled by the first two camps.[31]

Most other commentators on the impact debate, including Flessa, Raup, and Benton, have tended to break the participants down into 'catastrophists', or those who support a catastrophic model of extinction (i.e., the Alvarez impact hypothesis), and 'gradualists', who subscribe to a gradual, terrestrial model of extinction cause.[32] The gradualist camp, according to this definition, incorporates the volcanists as well as adherents of other endogenous models, such as regression, climate change, habitat fragmentation, etc. Some authors, most notably Flessa, add a third category: supporters of a 'step-wise' model of extinction, in which individual extinctions are abrupt and catastrophic, but extinctions occur in diachronous steps or stages which can make the overall pattern appear gradual.[33] Again, none of these authors has attempted an in-depth analysis of the arguments made specifically by vertebrate paleontologists against the Alvarez hypothesis, except to state that they, more than any other scientific group as a whole, have tended to reject the impact hypothesis and support a gradualist point of view.

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[31] Glen, "A manifold current upheaval in science," 190-209.
[32] Karl Flessa, "The 'facts' of mass extinctions," in Sharpton and Ward, eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*, 1.
Benton, "Scientific methodologies in collision," 371-400.
David M. Raup, *The Nemesis Affair: A Story of the Death of Dinosaurs and the Ways of Science* (New York: W. W. Norton & Company, Inc., 1986), 29-45.
[33] Karl Flessa, "The 'facts' of mass extinctions," 1.

The purpose of this thesis is to explore the role(s) of vertebrate paleontologists within the impact/mass extinction debate and to determine the reasons behind their informal reactions, their published views, and their silence. These reasons take the form of theoretical, social, and scientific objections to the Alvarez theory itself, its theoretical presuppositions, its defenders, and their manner of defense. It is crucial to examine what vertebrate paleontologists have said during the course of this debate precisely because – until now – their objections have gone largely unheard.

First, Chapter 1 provides a historical background of the science of vertebrate paleontology and its theoretical suppositions, and a brief summary of important issues in vertebrate paleontology just prior to and contemporaneous with the impact debate. Although these theories predisposed vertebrate paleontologists and other earth scientists to be skeptical of the impact theory, there were larger forces at work, which are the focus of Chapters 3 and 4.

Chapter 2 presents the story of the Alvarez hypothesis: a brief summary of the pre-Alvarez state of K-T mass extinction research, the research that led to the proposal of the Alvarez hypothesis, the initial publication, and the flurry of response that ensued. This section cannot be an exhaustive history of the entire impact/mass extinction debate, which to date involves upwards of 2,500 articles, reviews, and books.[34] Instead, through a brief analysis of the major publications on the subject, I present the main ideas, publications, and players in sufficient detail to provide a general characterization of the debate, and demonstrate the current understanding of the status of the impact/extinction hypothesis and its ramifications. I also present some of the arguments and attitudes of the Alvarez team.

In the third chapter, I explore in detail the contributions of vertebrate paleontologists to the debate. A brief analysis of articles published in *Science*, which became the principal forum of scientific publication for the debate,[35] provides a context

[34] Glen, "What killed the dinosaurs?" 354. Glen noted that the number of articles, books, and reviews published on the subject of the mass extinction debates was in excess of 2,000. That number has certainly continued to increase in the thirteen years since Glen's observation, but an up-to-date bibliography of relevant publications does not exist.
[35] Charles Officer and Jake Page, *The Great Dinosaur Extinction Controversy* (Reading: Helix Books, 1996), 96-97. Officer and Page, who opposed the Alvarez hypothesis in favor of their own volcanist explanation for the K-T extinctions, stated "*Science* magazine became the publication medium of choice for

for these contributions. Especially important is the work of mammal paleontologist William A. Clemens, who has been identified as the most vocal critic of impact theory among vertebrate paleontologists, and dinosaur paleontologist Dale A. Russell, who is likewise recognized as its most staunch supporter. I also discuss and compare the results of the various surveys and polls (including a survey conducted by the author) made over the past twenty years which have attempted to quantify the reactions of scientists of various disciplines to the Alvarez hypothesis. This survey analysis shows that while vertebrate paleontologists came to accept that a bolide impact had occurred, they did not accept that it was the (sole) cause of the Cretaceous-Tertiary mass extinction.

In Chapter 4 the reactions of vertebrate paleontologists to the Alvarez hypothesis and the subsequent debate will be discussed and interpreted. These reactions have been broken down into several social, theoretical, and scientific grounds on which vertebrate paleontologists rejected the Alvarez impact/extinction hypothesis. These grounds do not represent a comprehensive list of all objections made by all scientists to the Alvarez hypothesis throughout the debate, which again are too numerous to explore fully. Rather, I have chosen to emphasize those points of contention that vertebrate paleontologists raised most often, and/or those which deal with evidence and issues which fall within the vertebrate paleontologists' domain.

Vertebrate paleontologists rejected the Alvarez impact hypothesis on the basis of its incompatibility with the scientific evidence of their discipline. This lack of scientific support was compounded by several theoretical presuppositions and social factors which made the Alvarez theory unappealing on these other levels as well as on evidentiary grounds. From this analysis, a clear picture emerges of the theoretical commitments held

those whose work supported the Alvarez hypothesis" (96-97). In response to accusations made by another volcanist, geologist Dewey McLean, of favoritism towards the Alvarez impact hypothesis, *Science* editor Daniel E. Koshland noted that "'freedom of speech' cannot mean 'equal space' for all points of view", and also maintained that "*Science*, in my opinion, has been impeccably fair and has accepted papers from both volcanists and those in favor of the impact hypothesis. If, over a period of time, the balance has shifted, that is because of the new data that have come in. The news coverage has necessarily reflected this shift." Daniel E. Koshland, Response to Letter by Dewey M. McLean, *Science* vol. 259, no. 5097 (February 12, 1993), 877.

by vertebrate paleontologists prior to – and desperately defended during – the impact debate, which shaped their interpretation of the fossil evidence, and provided the rationale for rejecting the Alvarez impact hypothesis.

Chapter 1: Vertebrate Paleontology and its Theoretical Presuppositions

Vertebrate paleontologists, by definition, are those scientists who use the fossil record to study the remains of animals with backbones. Because these fossil remains are found in rocks, paleontologists must to some degree be geologists as well as biologists. Although the academic processes by which vertebrate paleontologists are trained and certified vary widely not only from country to country but also from institution to institution, it can generally be said that most, if not all, practicing vertebrate paleontologists have been schooled in the basic principles of geology (including uniformitarianism) and of biology (including Darwinian evolution).[36] Because these basic principles form the paleontological paradigm against which new theories, like the Alvarez impact/extinction hypothesis, are judged, it is necessary to examine them in some detail.

Uniformitarianism was first proposed by Scottish geologist James Hutton (1726-1797) in the late 1700s, refined by British geologist Charles Lyell (1797-1875) in his landmark treatise *Principles of Geology,* published in three volumes in 1830, and finally named by William Whewell (1794-1866) in an 1832 review of Volume Two of Lyell's opus. Uniformitarianism is often summed up with the phrase "The present is the key to the past." Simply stated, uniformitarianism tells us that when we attempt to explain past events, as documented in the geological record, we should only invoke processes which can be observed to operate in the present. Hutton wrote in 1795:

> Not only are no powers to be employed that are not natural to the globe, no action to be admitted of except those of which we know the principle, and no extraordinary events to be alledged [sic] in order to explain a common appearance... we are not to make nature act in violation to that order which we actually observe... chaos and confusion are not to be introduced into the order of nature, because certain things appear to our partial views as being in some disorder. Nor are we to proceed in feigning causes, when those seem insufficient which occur in our experience.[37]

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[36] The Society of Vertebrate Paleontology (SVP) website, PaleoFAQs page: <www.vertpaleo.org/education/faqs.html>, viewed July 11, 2003.

[37] James Hutton, *Theory of the Earth, With Proofs and Illustrations, Vol III.* Sir Archibald Geikie, ed., (The Geological Society of London, 1997), 547.
See also: John Playfair, *Illustrations of the Huttonian Theory of the Earth* (Edinburgh: William Creech, 1802).

This quotation demonstrates Hutton's conviction that events documented in the fossil record can and should be explained only by recourse to known *terrestrial* processes which follow established laws. For his part, Lyell was also confident that, given sufficient geological time, the gradual processes of erosion and uplift occurring today could create all manner of climatic and biological conditions observable in the geologic and fossil record. In a letter to British physician and amateur vertebrate paleontologist Gideon Mantell, dated February 15, 1830, Lyell wrote:

> [W]ithout help from a comet, or any astronomical change… but all easily and naturally. I will give you a receipt for growing tree ferns at the pole, or if it suits me, pines at the equator; walruses under the line, and crocodiles in the arctic circle. [38]

As the above quotation indicates, Lyell believed that gradual geological processes, if given sufficient time to operate, could produce even the most apparently unusual situations – such as tropical conditions (complete with ferns and crocodiles) at the poles, or temperate conditions (supporting pine trees) at the equator. Such conditions – radically different from the climatic distribution of the present day – did not require radical, catastrophic explanations, according to Lyell, but only normal, gradual geological processes and time enough for them to operate. Like Hutton, Lyell also suggested that terrestrial causes are sufficient and extraterrestrial factors, such as comets, are not necessary. Geologist and historian of science Ursula B. Marvin points out that Lyell's mention of a comet is a "sly reference" to the catastrophist theories of William Whiston (1667-1752), who invoked cometary impacts to explain not only the Biblical deluge but also the origin of the Earth itself.[39] In fact, uniformitarianism as described by Lyell was originally codified to stand in direct opposition to Biblical catastrophism, championed by Georges Cuvier (1769-1832), a famous French anatomist and – somewhat ironically – the father of vertebrate paleontology. Cuvier believed that the Earth had suffered a series of cataclysmic extinctions, immediately followed by episodes of special creation, in which

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[38] Charles Lyell, *Life, Letters and Journals of Sir Charles Lyell, Bart: Author of 'Principles of Geology', &c. Edited by his sister-in-law, Mrs. Lyell. In Two Volumes, With Portraits* (London: John Murray, Albemarle Street, 1881), vol. 1, 262.

God created new species to replace the ones that had been destroyed. These new species did not evolve in any sense but simply appeared, fully developed, in the fossil record. The triumph of uniformitarianism over Biblical catastrophism was really the beginning of scientific geology, since it removed all recourse to unexplainable supernatural causes and placed geology strictly within the realm of the physical world.

As Marvin points out, it is clear from the writings of Hutton and Lyell that uniformitarianism describes not only a constancy of physical laws and processes, but also a constant and *gradual rate* by which these laws and processes operate. Lyell recognized that the former (constancy of process) did not logically necessitate the latter (constancy of rates), but he firmly believed both suppositions to be true, and also incorporated the idea of constant rates to more firmly oppose the abrupt and discontinuous changes inherent in the catastrophist model.[40] Darwin, deeply influenced by Lyell, also incorporated this idea of gradual and incremental change into his theory of evolution.

Charles Darwin was familiar with the work of Charles Lyell before he published *On the Origin of Species By Means of Natural Selection* in 1859.[41] According to Janet Browne, Darwin used Lyell's concept of uniformitarianism to interpret much of what he saw on the famous voyage of the *Beagle*.[42] Certainly the idea of slow, continuous change, using forces now in action, was a fundamental principle in his theory of evolution, which today is often referred to as phyletic gradualism. Darwin's model holds that evolution is a continuous and gradual process, in which one species blends almost imperceptibly into another by the slow accumulation of selected characteristics.

According to invertebrate paleontologist Stephen Jay Gould, phyletic gradualism was proposed to stand in opposition to the theories of the creationists, since the creation of species, or even a series of distinct creations, is necessarily a discontinuous process.[43]

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39 Ursula B. Marvin, "Impact and its revolutionary implications," in Sharpton and Ward, eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*, 148.
40 Stephen Jay Gould, "Is uniformitarianism necessary?" *American Journal of Science* vol. 263 (March 1965), 224.
41 Charles Darwin, *On the Origin of Species by Means of Natural Selection or the Preservation of Favoured Races in the Struggle for Life* (New York, Penguin Books USA Inc., 1958).
42 Janet Browne, "Darwin's botanical arithmetic and the 'principle of divergence'," *Journal of the History of Biology* vol. 13 (1980), 53-89.
43 Gould, "Is uniformitarianism necessary?", 224.

If the fossil record were to reveal creatures which appeared to be intermediate between two species, as it has occasionally done, this would support Darwin's theory of phyletic gradualism, but would refute the idea of instantly-created, unchanging species. On the other hand, any lack of intermediary forms would not necessarily have the opposite effect of undermining Darwin's theory and supporting creationism, since this lack could be explained away by invoking gaps in the fossil record. This technique of assuming that discontinuous changes in the fossil record indicated gaps or missing sections was in fact employed by Darwin to bolster his theory of gradual, continuous change. The following passage from the *Origin of Species* demonstrates Darwin's intellectual debt to Lyell, his opposition of creationism, and also his firm belief in gradualism:

> Let us now see whether the several facts and laws relating to the geological succession of organic beings accord best with the common view of the immutability of species, or with that of their slow and gradual modification, through variation and natural selection.
>
> New species have appeared very slowly, one after another, both on the land and in the waters. Lyell has shown that it is hardly possible to resist the evidence on this head in the case of the several tertiary stages; and every year tends to fill up the blanks between the stages, and to make the proportion between the lost and existing forms more gradual.[44]

This last point is worth repeating, since it became such a fundamental assumption in biology, geology, and paleontology: Lyell, Darwin, and virtually all earth scientists after them, at least until the 1960s or so, interpreted any evidence of discontinuous or abrupt change in the fossil record as a priori evidence of a gap, a horizon from which a substantial chunk of the fossil record was missing. In other words, they believed that if the fossil record were continuous and displayed the true history of life in its entirety, scientists would be able to see in it gradual evolutionary change over long periods of time. For example, in the third volume of his *Principles of Geology*, Lyell had this to say about the 'apparent' mass extinction at the end of the Cretaceous period:

> There appears, then, to be a greater chasm between the organic remains of the Eocene and Maestrict beds, than between the Eocene and Recent strata… It is not improbable that a greater interval of time may be indicated by this greater dissimiliarity of fossil remains… so we may,

[44] Darwin, *On the Origin of Species*, 320.

> perhaps, hereafter detect an equal, or even greater series, intermediate between the Maestrict beds and the Eocene strata.[45]

In the above passage, what Lyell refers to as the Maestrict beds are the rocks representing the latest Cretaceous period, while the Eocene strata were the first rocks of the Tertiary period. The Recent strata, as the name suggests, are the youngest rocks in the entire record, covering the period from one million years ago to the present. Lyell is suggesting, therefore, that there is a missing section of rock at the K-T boundary equal to or greater than the 64 or 65 million years recorded in the rocks spanning the Eocene to the present day.

Darwin expressed much the same opinion on the abrupt faunal turnover visible at the Permian-Triassic boundary, as well as at the K-T boundary:

> With respect to the apparently sudden extermination of whole families or orders, as of Trilobites at the close of the paleozoic period [i.e., at the end of the Permian period] and of Ammonites at the close of the secondary period [i.e., at the end of the Cretaceous period], we must remember what has already been said on the probable wide intervals of time between our consecutive formations; and in these intervals there may have been much slower extermination.[46]

Both Lyell and Darwin believed so strongly in gradualism that they preferred to believe the K-T boundary encompassed a gap in time equal to the entire Cenozoic Era (Eocene to present), during which gradual evolutionary change occurred, rather than that this gap – for which they had no independent evidence – might not exist, and the apparently abrupt biological change across the K-T boundary might be real.

Darwin's adoption of gradualism into his theory of evolution brought paleontology and biology as well as geology fully under the umbrella of Lyellian uniformitarianism. In the 1930s, Darwinian evolution was joined with Mendelian genetics and population studies in what is termed the modern synthesis. Although Mendel's genetics involved the mutation and inheritance of discrete, discontinuous characters, it was recognized that these characters could occur in so many varied forms as to provide the appearance of continuous, gradual change between individuals. Population genetics recognized the importance of geographical variation in creating differing

[45] Lyell, *Principles of Geology*, vol. 3, p. 328.

selection pressures, leading to geographical variations among populations of the same species. The modern synthesis emphasized that most speciation events likely followed from the geographical isolation of a small population, but the tempo of such speciation events was still thought to be gradual.[47] Thus, with the continued acceptance of the gradualist paradigm, the natural sciences remained under the umbrella of uniformitarianism for almost a century.

During the mid-20th century, the earth sciences were shaken by three revolutionary changes, one of which would strengthen the uniformitarian paradigm, and two of which would weaken it. The first of these changes was the continental drift/plate tectonics revolution. Continental drift, proposed in the early 1900s, suggested that the Earth's continents floated on top of the oceanic crust and had been in vastly different positions at various points throughout the Earth's history. Plate tectonics, on the other hand, expressed the slightly different concept that the Earth's crust, including continental and oceanic sections, are divided into a series of plates which slowly grind against and slide over and under one another.[48] There have been many books and articles written about the history of continental drift, in particular about why it was rejected by the majority of geologists for nearly fifty years, until it was finally embraced, in its new incarnation as plate tectonics, in the 1960s.[49] Most historians of continental drift agree that, when it was finally adopted, continental drift served to bolster or affirm the principle of uniformitarianism.[50] As Marvin writes:

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[46] Darwin, *Origin of Species*, 327.
[47] Peter J. Bowler, *Evolution: The History of an Idea*, Revised Edition (Berkeley: University of California Press, 1989), 307-318.
[48] William Glen, *Continental Drift and Plate Tectonics* (Columbus: Bell & Howell Company, 1975), 1-2.
[49] William Glen, *The Road to Jaramillo: Critical Years of the Revolution in Earth Science* (Stanford: Stanford University Press, 1982).
Anthony Hallam, *A Revolution in the Earth Sciences: From Continental Drift to Plate Tectonics* (Oxford: Clarendon Press, 1973).
Homer E LeGrand, *Drifting Continents and Shifting Theories: The Modern Revolution in Geology and Scientific Change* (Cambridge and New York: Cambridge University Press, 1988).
Oreskes, *The Rejection of Continental Drift*.
Ursula B.Marvin, *Continental drift: the evolution of a concept* (Washington, D.C.: Smithsonian Institution Press, 1973).
[50] Glen, "Observations on the mass-extinction debates," 147.
John A. Van Couvering, "Introduction," in W. A. Berggren and John A. Van Couvering, eds., *Catastrophes and Earth History: The New Uniformitarianism* (Princeton: Princeton University Press, 1984), 4.
Some historians, however, take the opposing stance. For example, historian of geology Naomi Oreskes, in her book *The Rejection of Continental Drift*, argued that the continental drift hypothesis was anti-

> [T]he geological sciences were engulfed by the plate tectonics revolution, which swept away the time-honored idea of fixed continents and replaced it with a vision of the Earth's lithosphere as a dynamic array of horizontally moving plates. At the time, the new global tectonics appeared to be an extremely radical departure from classical geology. In retrospect, however, we can see that plate tectonics, as envisioned today, is fully consistent with the uniformitarian concepts inherited from Hutton and Lyell: the plates gradually split, slide, and suture, driven by forces intrinsic to the globe.[51]

At the same time that plate tectonics was strengthening the uniformitarian paradigm, however, other forces were weakening it, one operating within geology, and one arising from evolutionary biology. As statistician and invertebrate paleontologist David M. Raup notes, geologists and paleontologists had learned as part of their training in the earth and physical sciences that although the solar system had suffered an 'early bombardment' of comet and asteroid impacts, this debris left over from the formation of the sun and planets had largely been cleared away, and no significant impacts were thought to have occurred in the last 500 million years – almost the entire history of life on Earth.[52] Although a few more recent impact craters were eventually acknowledged, beginning in 1929 with one of the most famous examples, Meteor Crater (or Barringer Crater) in Arizona, most crater-like features on Earth were explained as 'cryptovolcanic' or 'cryptoexplosion' structures: craters produced by some hypothetical and unexplained crustal process, in which an eruption of sorts occurs but no lava is released.[53] In the tradition of Hutton and Lyell, who 'alleged no extraordinary events' and 'scorned the help of a comet', the geologists of the early and mid-1900s preferred to believe in a

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uniformitarian because it required that the past was radically different from the present, with continents in completely different configurations (p. 201). Paleontologist Norman D. Newell, while not explicitly stating that continental drift contravened uniformitarianism, wrote: "The development of the paradigm of plate tectonics has had a salutary effect on geological thought by opening up the way to world episodes of diastrophism and revolutionary geographic, as well as climatic, changes. Thus, for the first time, the great oscillations in climate and the sweeping changes in habitat that had already been identified by nineteenth-century geologists as probable causes of mass extinctions are provided with a theoretical mechanism." (Norman Newell, "Mass extinction: unique or recurrent causes?" in Berggren and Van Couvering, eds. *Catastrophes and Earth History: The New Uniformitarianism,* 115-127.)

[51] Marvin, "Impact and its revolutionary implications," 153.

[52] David M. Raup, *Extinction:Bad Genes or Bad Luck?* (New York and London: W. W. Norton & Company, 1991), 157-158.

[53] Marvin, "Impact and its revolutionary implications," 152.

terrestrial cause for these craters, and were comfortable in their assurance that impacts had not had much, if any, effect on life and its evolution.[54]

This assurance, while not destroyed until the advent of the Alvarez hypothesis in the 1980s, was perceptibly weakened with the dawn of the space program, following World War II. Telescopic observations of the Moon, and eventually rock samples brought back by the Apollo astronauts, demonstrated conclusively that the vast majority of lunar craters were of impact, not volcanic, origin; and though many did date from the period of early bombardment, many others were more recent. Increasing interest in the rest of the solar system showed that all of the rocky planets and moons were heavily cratered, and evidence of other catastrophic events also came to light, such as the flood-induced scablands of Mars.[55]

Uniformitarianism was being challenged on another front simultaneously, by Harvard invertebrate paleontologists Stephen Jay Gould and Niles Eldredge. In 1965, Gould published a landmark article entitled "Is uniformitarianism necessary?"[56] In this article, published in the *American Journal of Science*, Gould argued that Lyellian uniformitarianism actually encompassed two different concepts, one of which could no longer be supported, and one of which applied to all sciences and was therefore redundant. What Gould called 'methodological uniformitarianism' was Lyell's uniformity of processes, which simply states that the physical and chemical laws which we observe to operate today have always been in effect. This belief is not unique to geology but describes a fundamental underpinning of science in general, and therefore, Gould argued, should not be held up as a principle unique to geology.[57]

What Gould labeled 'substantive uniformitarianism', on the other hand, was the idea that processes in the geological past must have operated at the same rates and intensities that we observe today. Gould argued that this form of uniformitarianism was not valid, and had merely been created to underpin Lyell's firm belief in gradual, continuous change. In fact, as Gould and (later) others pointed out, rare and seemingly catastrophic events, including earthquakes, tsunamis, and even extraterrestrial impacts,

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[54] *Ibid.*
[55] Walter Alvarez, *T. rex and the Crater of Doom*, (New York: Vintage Books, 1997), 51-53.
[56] Gould, "Is uniformitarianism necessary?" 223-228.

are not unscientific because they operate under the same laws of physics and chemistry as the more usual, gradual processes.[58]

In 1972, Eldredge and Gould challenged Darwin's model of phyletic gradualism with their own theory of punctuated equilibrium.[59] By the 1970s, it was becoming increasingly apparent that invoking sedimentary gaps to explain the lack of transitionary forms between species was an ad hoc and ultimately unsatisfactory solution. Although there certainly *are* gaps in the fossil record, continued fieldwork never seemed to make them any smaller, at least in terms of narrowing evolutionary gaps. Even when missing 'blanks' could be filled in with newly discovered geological sections, the expected intermediate forms of fossils were (usually) not there. It was becoming increasingly apparent that a continued theoretical commitment to Darwinian gradualism would necessitate the continual invocation of gaps as large as or larger than the known sections of the fossil record, which began to seem absurd.

In answer to this theoretical dilemma, Eldredge and Gould proposed their theory of punctuated equilibrium. They suggested that the evolution of species is a process of abrupt and discontinuous change. According to this model, a species as a whole does not normally evolve in any linear, even if gradual way; in fact, most of the time a species remains fairly static. If, however, a small population of the species becomes isolated from the main population in such a way that it experiences new conditions, it will rapidly evolve according to these new selective pressures, until it becomes a new species. The idea of speciation occurring among small splinter populations is not inherently anti-Darwinian, and was in fact suggested by Darwin in the *Origin* and further emphasized during the modern synthesis. However, the idea that such speciation events occur rapidly and are interspersed with long periods of stasis is incompatible with phyletic gradualism and with uniformitarianism as intended by Lyell.

It would seem that the work of Gould, Eldredge, and the Apollo astronauts should have signaled the demise of uniformitarianism. Indeed, despite the mitigating effects of

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[57] *Ibid.*, 227.
[58] *Ibid.*, 226.
[59] Niles Eldredge and Stephen Jay Gould, "Punctuated equilibria: an alternative to phyletic gradualism," in Thomas J. M. Schopf, ed., *Models in Paleobiology* (San Francisco: Freeman, Cooper & Company, 1972): 82-115.

plate tectonics, by 1980 the recognition of Phanerozoic impacts and the advent of punctuated equilibrium had weakened uniformitarianism to the extent that when the Alvarez hypothesis was proposed, it was not immediately ignored by members of the earth science community – as had been every prior theory of mass extinction by extraterrestrial causes proposed over the past two hundred years.

The idea of an extraterrestrial cause for the K-T extinction or the Frasnian-Fammenian extinction had been put forth over the past few decades by a few scientists, although none of them had been taken seriously, in large part because none of them suggested a way to test their hypotheses. The well-respected German paleontologist Otto Schindewolf suggested in the 1950s and 60s that some form of cosmic radiation, perhaps from a supernova, could have caused mass extinctions on Earth.[60] Cambridge physicist Wallace Tucker and his colleague K. D. Terry published a theory in 1968 that radiation from a nearby supernova might destroy most of the Earth's ozone layer, which would have an adverse effect on life.[61] Likewise, in his presidential address to the Paleontological Society in 1969, subsequently published in the *Journal of Paleontology* in 1970, paleontologist Digby J. McLaren invoked a bolide impact to account for the abrupt and catastrophic mass extinction that occurred between the Frasnian and Fammenian stages of the Devonian Period, approximately 355 million years ago. Although McLaren was a respected paleontologist, his theory was not taken seriously, perhaps because it was buried in a larger discussion of how to properly define stratigraphic boundaries, because McLaren offered no proof of his hypothesis nor any suggestions for testing it, and finally because his theory purported to explain the extinction of various shelly marine organisms, which did not have the universal appeal of the dinosaurs.[62]

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[60] See for example:
Otto H. Schindewolf, "Uber die moglichen Ursachen der grossen erdeschichtlichen Faunenschnitte," *Neus Jahrb. Geol. Pal.*, Monatsheft 10 (1955): 457-465.
Otto H. Schindewolf, "Neokatastrophismus?" *Zeitschrift der Deutschen Geologischen Gesellschaft* vol. 114, no. 2 (1962): 430-445.
These papers by Schindewolf are discussed in:
Digby J. McLaren, "Presidential address: time, life, and boundaries," *Journal of Paleontology* vol. 44, no. 5 (September 1970): 811.
D'Hondt, "Theories of terrestrial mass extinction by extraterrestrial objects," 157-158.
[61] K.D. Terry and Wallace Tucker, "Biological effects of supernovae," *Nature* vol. 159 (1968): 421-423.
[62] Elisabeth Clemens, "The impact hypothesis and popular science," 102.

As the mounting physical evidence arose in the wake of the Alvarez proposal, and as the hold of uniformitarianism over their discipline weakened, most earth scientists came to accept that an impact had occurred, and that it had probably caused or at least played a significant role in the Cretaceous-Tertiary mass extinction. Although vertebrate paleontologists still retained deep commitments to uniformitarianism and gradualism, as arbiters of both geological and evolutionary processes, they too were eventually convinced that a bolide impact had taken place. However, not even the changes brought about by Eldredge and Gould's work on punctuated equilibrium, Gould's deconstruction of uniformitarianism, and the recognition of Phanerozoic impacts, or even the acceptance of a K-T bolide impact, could sway the allegiances of vertebrate paleontologists to a catastrophic extinction theory – not when they had other objections to the Alvarez theory. As we shall see in Chapter 3, while vertebrate paleontologists came to accept that a bolide impact had taken place, they almost universally rejected the extinction part of the Alvarez hypothesis, and for the most part, abstained from participating in the ensuing mass extinction debate. First, however, it is necessary to describe the work and background of the Alvarez team in further detail, in order to provide a context for the objections raised by vertebrate paleontologists. This discussion of the Alvarez team and their work is the subject of Chapter 2.

Chapter 2: The Alvarez Hypothesis and the Alvarez Team

The research that Walter Alvarez conducted in Gubbio, Italy, the eventual involvement of the rest of the Alvarez team, and the publication of their 1980 *Science* paper is a story that has been detailed often, by members of the Alvarez team themselves as well as other researchers.[63] Therefore it is only necessary to provide a summary of that well-known story, and then focus on the social interests and biographical factors that influenced the Alvarez team's actions and reactions in the debate that followed the publication of their paper. An overview of the response of the scientific community at large to the Alvarez hypothesis will follow, to provide a context for the role of vertebrate paleontologists within this debate.

Luis W. Alvarez was born in San Francisco, California, on June 13, 1911. He received his B.Sc. in 1932, his M.Sc. in 1934, and his Ph.D. in 1936, all in physics at the University of Chicago. Alvarez spent most of his career at the Lawrence Berkeley Laboratory at the University of California at Berkeley, although he also worked briefly at

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[63] The following sources provide detailed narration of the Alvarez team's research and initial publication. Some include biographical material as well:
Luis Alvarez, *Alvarez: Adventures of a Physicist*, 251-267.
Walter Alvarez, "Toward a theory of impact crises," *Eos* vol. 67, no. 35 (September 2, 1986): 649, 653-655, 658.
Walter Alvarez, *T. rex and the Crater of Doom*, 59-81.
Frank Asaro, "The Cretaceous-Tertiary iridium anomaly and the asteroid impact theory," in W. Peter Trower, ed. *Discovering Alvarez: Selected Works of Luis W. Alvarez With Commentary by his Students and Colleagues* (Chicago and London: University of Chicago Press, 1987), 240-242.
Richard Muller, *Nemesis, The Death Star: The Story of a Scientific Revolution* (New York: Weidenfeld & Nicolson, 1988), 39-85.
As well as summarizing the Alvarez team's research, like the above sources, Raup recalls his own initial reaction to the Alvarez hypothesis through a series of quotations, and also summarizes the initial response of the scientific community at large to the hypothesis:
Raup, *Nemesis Affair*, 61-74.
In the following chapter, historian of science William Glen provides a breathless summary of the scientific evidence, interpretations, and counter-theories which arose in the first decade after the proposal of the Alvarez hypothesis:
William Glen, "Chapter 1: What the impact/volcanism/mass-extinction debates are about," in Glen, ed., *The Mass-Extinction Debates*, 7-38.

the MIT Radiation Laboratory (1940-1943), the University of Chicago Metallurgical Laboratory (1943), and the Los Alamos Laboratory (1944-1945).[64] His father, Walter C. Alvarez, was a general medical practitioner well known for his newspaper column "Ask Dr. Alvarez." As Luis Alvarez's colleague and former student, astrophysicist Richard Muller, noted in his book on the periodic impact hypothesis, Alvarez followed his father's example by becoming a "general practitioner of physics."[65] Luis learned another important lesson from his father: Alvarez senior had narrowly missed winning a Nobel Prize in medicine. He had thought of treating anemia with liver, but never followed through on this idea, and several years later, another doctor was awarded the Nobel Prize for exactly this research. Walter C. Alvarez – who never came so close to glory again - made sure Luis learned from his example.[66] Indeed, Luis Alvarez suffered similar defeats on at least two occasions. He came very close to discovering fission, and later, to discovering the emission of secondary neutrons during fission, but in both cases he had not continued his observations long enough to make the crucial discovery. Eventually, Luis was awarded the Nobel Prize for Physics in 1968 for his discoveries with bubble chambers. Trained as a particle physicist, Alvarez made a host of discoveries in this field as well as other areas of physics, and was responsible for several inventions, in areas ranging from optics to aircraft guidance systems.[67] Alvarez invented the triggering system used on the atomic bomb that was dropped on Hiroshima, and later was one of five scientists who testified that their team leader, Dr. Robert Oppeheimer, had become a security risk to the atom bomb project. Author Nuel Pharr Davis's account of a conversation one of the project leaders had with Luis Alvarez serves to illustrate Alvarez's tendency to view things in black-and-white, right or wrong terms:

> What [Alvarez] seemed to be saying was Oppenheimer and I often have the same facts on a question and come to opposing decisions – he to one, I to another. Oppenheimer has high intelligence. He can't be analyzing and

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[64] W. Peter Trower, ed., "Appendix A: Biography", 257- 259, *Discovering Alvarez: Selected Works of Luis W. Alvarez, with Commentary by His Students and Colleagues* (Chicago and London: The University of Chicago Press, 1987), 257.
[65] Muller, *Nemesis The Death Star*, 25.
[66] *Ibid.*, 26.
[67] Trower, ed., "Appendix A," 257.

> interpreting the facts wrong. I have high intelligence. I can't be wrong. So with Oppenheimer it must be insincerity, bad faith – perhaps treason?[68]

As volcanism proponent Charles Officer pointed out in his 1996 book (coauthored with science writer Jake Page), this kind of all-or-nothing reasoning explains at least in part why Alvarez had so little understanding of and so much frustration with the views of vertebrate paleontologists.[69] For Alvarez, the iridium (and other geochemical evidence) proved the bolide impact, and the synchroneity of the impact with the K-T mass extinction proved the former caused the latter. Nothing could be more simple to understand – and he could not comprehend why the vertebrate paleontologists refused to acknowledge such an obvious and simple truth. Alvarez expressed his frustration at several points throughout the impact debate. For example, when Alvarez's attempts to demonstrate the statistical insignificance of the two-metre gap between the last known dinosaur fossils and the iridium horizon failed to convince paleontologists that the impact had killed the dinosaurs, he commented:

> I'm really quite puzzled [that] knowledgeable paleontologists would show such a lack of appreciation for the scientific method. ... I'm really sorry to have spent so much time on something the physicists in the audience will say is obvious."[70]

Walter Alvarez was the first of Luis Alvarez's four children, born on October 3, 1940. Walter Alvarez has written that it was his mother, Luis's first wife, Geraldine, who got him interested in geology, through family trips and vacations.[71] Walter went away to college and graduate school at Princeton, where he earned a Ph.D. in geology. Walter did not see much of Luis, and did not know his scientific work well at all; for his part, Luis found geology rather provincial and uninteresting. This would change with Walter's appointment as Associate Professor to the Geology Department at Berkeley, and his work on the K-T boundary in Gubbio, Italy.[72]

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[68] Nuel Pharr Davis, *Lawrence and Oppenheimer* (New York: Simon and Schuster, 1968), 314.
[69] Officer and Page, *The Great Dinosaur Extinction Controversy*, 82.
[70] Robert Jastrow, "The dinosaur massacre: a double-barreled mystery," *Science Digest* vol. 91, no. 9 (September 1983), 52.
[71] Walter Alvarez, *T. rex and the Crater of Doom*, 60.
[72] *Ibid.*

Walter Alvarez originally became interested in the scaglia rossa limestones near Gubbio, Italy, in the early 1970s, in the hopes of using the orientation of magnetic minerals within these rocks as a way to test for continental drift. Although this line of inquiry did not prove fruitful, Alvarez was able to pool his efforts with a team of American and Italian geologists, who jointly mapped out the series of geomagnetic reversals detailed in the Gubbio rocks.[73]

The limestones at Gubbio that Walter Alvarez studied through the mid-1970s happened to span the Cretaceous-Tertiary boundary. In these particular rocks, the boundary was especially distinctive (Plate 1). The latest Cretaceous limestones, below the boundary, contained many large and varied foraminifera, tiny marine planktonic organisms that secrete intricate shell-like tests of calcium carbonate. The boundary itself was represented by a thin clay layer containing no limestones or fossils. Limestone deposition appeared to have resumed above the clay layer, but these earliest Tertiary limestones, although nearly identical to those only centimetres below, were virtually devoid of foraminifera (Plate 2).[74]

As a geologist, Alvarez already knew that the K-T boundary marked the time of the second-largest mass extinction in the fossil record, a time when as many as 75% of the species then on Earth had disappeared. He knew also that the most famous group of animals to become extinct around this time was the dinosaurs. When he took a position in the geology department at Berkeley in 1977, Walter Alvarez was intrigued enough by the boundary section to bring a piece of it to show to his father, physicist Luis Alvarez.[75] Father and son alike saw the boundary clay as an intriguing mystery: what could have happened, when that clay was deposited, that affected tiny marine foraminifera and huge terrestrial dinosaurs at the same time?

They decided the first step was to figure out how long it had taken for the clay layer to be deposited. Luis Alvarez suggested they measure the amount of meteoritic

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[73] *Ibid.*, 34-40.
[74] *Ibid.*, 40-42.
[75] This pivotal moment, when Luis Alvarez looked at his son's boundary rock sample and first became intrigued by the mystery of the Cretaceous-Tertiary mass extinction, has been described by Alvarez senior, Alvarez junior, and Luis Alvarez's colleague Richard Muller:
Luis Alvarez, *Alvarez: Adventures of a Physicist*, 252.
Walter Alvarez, *T. rex and the Crater of Doom*, 59-60.

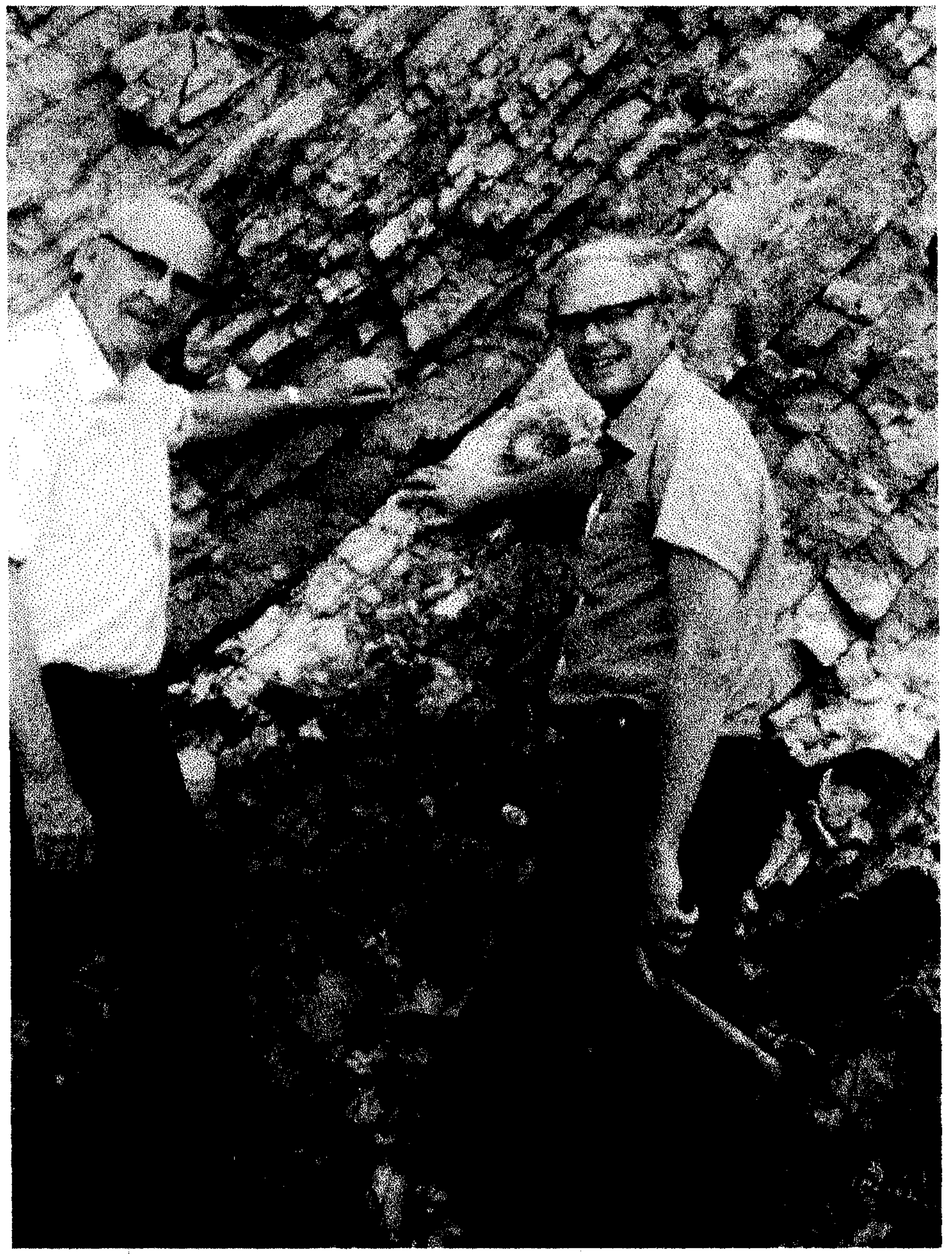

Plate 1. Luis Alvarez, Walter Alvarez, and the K-T Boundary at Gubbio, Italy

Luis Alvarez (left) stands with one hand on the basal rocks of the Tertiary period; his son Walter's hand is on the uppermost rocks of the Cretaceous period. Just above Walter's outstretched fingers is the dark boundary clay layer in which the Alvarez team found an unusually high concentration of the element iridium. The rock layers were laid down horizontally, millions of years ago, but have been tilted by subsequent geological processes.

Source: Lawrence Berkeley National Laboratory Image Library, <http://imglib.lbl.gov/ImgLib/COLLECTIONS/BERKELEY-LAB/PEOPLE/INDIVIDUALS/images/96703338.lowres.jpeg>

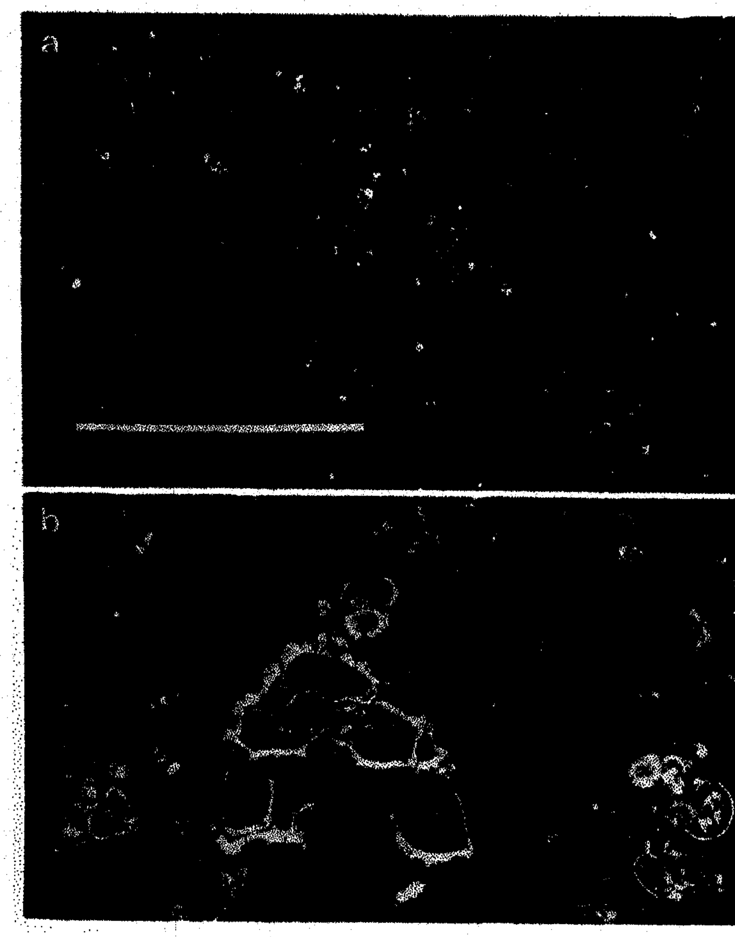

Fig. 1. Photomicrographs of (a) the basal bed of the Tertiary, showing *Globigerina eugubina*, and (b) the top bed of the Cretaceous, in which the largest foraminifer is *Globotruncana contusa*. Both sections are from the Bottaccione section at Gubbio; they are shown at the same scale and the bar in (a) is 1 mm long.

Plate 2. K-T Boundary Section from Gubbio, Italy

This photograph is from the 1980 *Science* paper in which the Alvarez team first proposed their impact/mass extinction theory. The large and intricate shells or tests visible in the bottom (Cretaceous) sample are absent from the top (Tertiary) sample directly above it. It was this evidence of an abrupt extinction among the foraminifera that caused Walter Alvarez, and later his father Luis Alvarez, to become so fascinated with the K-T extinction.

Source: Alvarez, Luis W., Walter Alvarez, Frank Asaro, and Helen V. Michel. "Extraterrestrial cause for the Cretaceous-Tertiary extinction: experimental results and theoretical interpretation." *Science* vol. 208, no. 4448 (June 6, 1980): 1095-1108.

material in the clay layer, since meteoritic dust falls on the Earth at a constant rate. They decided to look for iridium, known to be a common constituent of asteroids. Alvarez senior enlisted two of his Berkeley colleagues, nuclear chemists Frank Asaro and Helen Michel, to use their technique of neutron activation analysis to measure the amount of iridium in the clay layer.[76]

To everyone's surprise, the boundary clay from Gubbio contained an enormous quantity of iridium. They had expected to find approximately one part per billion of iridium if the clay had been deposited very slowly, over several thousand years, or essentially no iridium if it had been deposited rapidly. Instead, the clay turned out to contain 9 ppb iridium – 90 times more than the highest amount they could have expected.[77] Walter Alvarez immediately set out to find a boundary sample from a different location which could also be tested for iridium. He collected a sample from the K-T boundary section known as the Fish Clay, at Stevns Klint, Denmark, which when analysed also proved to contain an elevated concentration of iridium.[78]

Their original question regarding the rate of deposition of the clay layer forgotten, the Alvarez team began seeking an explanation for the iridium anomaly. They initially thought they had stumbled upon a proof of the supernova hypothesis.[79] Several prominent scientists, including Columbia University physicist Malvin A. Ruderman and dinosaur paleontologist Dale A. Russell, who had completed his master's degree at Berkeley, had published several papers throughout the 1970s suggesting that radiation from a nearby supernova explosion had caused the K-T extinction.[80] Such an explosion would be expected to bombard the Earth with several rare heavy elements, including iridium, as well as the lethal radiation. The Alvarez team immediately thought of a way to test the supernova hypothesis: they would examine the boundary clay for traces of

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Muller, *Nemesis, The Death Star*, 40-42.
[76] Asaro, "The Cretaceous-Tertiary iridium anomaly," 240.
[77] *Ibid.*, 241.
[78] Walter Alvarez, *T. rex and the Crater of Doom*, 70.
[79] *Ibid.*, 71.
[80] See for example:
Dale A. Russell and Wallace Tucker, "Supernovae and the extinction of the dinosaurs," *Nature* vol. 229 (February 19, 1971): 553-554.
Malvin A. Ruderman, "Possible consequences of nearby supernova explosions for atmospheric ozone and terrestrial life," *Science* vol. 184, no. 4141 (June 7, 1974): 1079-1081.

plutonium-244. This is a radioactive isotope of plutonium with a relatively short half-life, of 83 million years. This half-life is short enough that any plutonium-244 present on the Earth at its formation would have completely decayed by now; however, the K-T boundary is only 65 million years old, so if any Pu-244 was deposited on Earth by a supernova at this time, some traces of it should remain.[81] Asaro and Michel began another neutron activation analysis, this time searching for plutonium-244.

The first series of tests showed a definite spike of Pu-244, but on the advice of Lawrence Berkeley Laboratory Deputy Director Earl Hyde, Asaro insisted on running another series of tests before announcing their results, just to be safe.[82] To the team's disappointment, the second series did not detect any Pu-244 at all, and Asaro eventually realized the plutonium from the first batch had come from a contaminated bottle of hydrofluoric acid which he had borrowed from another laboratory during the first test series.[83] The Alvarez team published their first round of papers on the iridium anomaly, as a falsification of the supernova extinction hypothesis, in mid- to late 1979.[84]

The absence of plutonium disproved the supernova hypothesis, but the anomalously high level of iridium still suggested an extraterrestrial source. Luis Alvarez immediately thought of an asteroid or cometary impact, but – since the whole experiment had begun with an examination of the K-T extinction – felt he needed to forge a causal link between an impact and the extinction of the dinosaurs, forams, and other victims of the mass extinction.[85] An impact would kill any creatures within a certain radius of the impact site, and an oceanic impact would create a huge tsunami that would devastate coastlines. But the Alvarez team needed a global killing mechanism, something that would affect terrestrial dinosaurs and marine plankton alike. Luis Alvarez recalled

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[81] Walter Alvarez, "Toward a theory of impact crises," 649.
[82] Walter Alvarez, *T. rex and the Crater of Doom*, 74.
[83] Muller, *Nemesis, The Death Star*, 58-59.
[84] Walter Alvarez, Luis W. Alvarez, Frank Asaro, and Helen V. Michel, "Anomalous iridium levels at the Cretaceous-Tertiary boundary at Gubbio, Italy: negative results of tests for a supernova origin," in W. K. Christensen and Tove Birkelund, eds., *Symposium, Cretaceous-Tertiary Boundary Events, II, Proceedings* (University of Copenhagen), 69.
Walter Alvarez, Luis W. Alvarez, Frank Asaro, and Helen V. Michel, "Experimental evidence in support of an extraterrestrial trigger for the Cretaceous-Tertiary extinctions," *Eos* vol. 60 (1979): 734.
[85] Luis Alvarez, *Alvarez: Adventures of a Physicist*, 255.
Walter Alvarez, *T. rex and the Crater of Doom*, 75.
Muller, *Nemesis, The Death Star*, 61.

reading an account by the Royal Society of London of the 1883 eruption of Krakatoa, a volcano in Indonesia.[86] The report indicated that sunsets as far away as London were colored bright red for many months after the eruption, presumably from the ash released into the air.[87] Alvarez realized that a bolide impact would send up a huge dust cloud, which the force of impact would transport ballistically around the world. By scaling up the effects of the Krakatoa explosion, Alvarez estimated that the impact-generated dust cloud would persist for several years, shutting down photosynthesis and collapsing marine and terrestrial food chains.[88] Satisfied that they had explained all of the end-Cretaceous extinctions as well as the iridium anomaly, the Alvarez team quickly began work on their seminal paper, which was submitted to *Science* in November of 1979.[89]

While the story of the Alvarez team's initial research has been described in great detail by the team themselves as well as by other scientists and students of the impact debate, much less has been written about the chronology of the publications, conferences, and personal interactions that followed this research. Although it was the 1980 article in *Science* that brought the Alvarez hypothesis to the attention of the scientific community at large, the asteroid hypothesis was actually announced in two prior venues: a University of California Lawrence Berkeley Laboratory Report (1979)[90] and the American Association for the Advancement of Science (AAAS) annual meeting in San Francisco in January, 1980.[91] Response was immediate and enthusiastic; indeed, several other scientists had been working on the same problem and had come to the same conclusion. Geologist Jan Smit and chemist Jan Hertogen published an article in the May 22, 1980 issue of *Nature* – the British equivalent of North America's *Science* – in which they reported an iridium anomaly in the K-T boundary layer at Caravaca, in southeast Spain, and also attributed it (and the K-T extinction) to a bolide impact.[92] In the same issue of

[86] Luis Alvarez, *Alvarez: Adventures of a Physicist*, 256.
[87] G. J. Symons, ed., *The Eruption of Krakatoa, and Subsequent Phenomena* (London: Royal Society, 1888).
[88] Luis Alvarez et al, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," 1105.
[89] Luis Alvarez, *Alvarez: Adventures of a Physicist*, 257.
Walter Alvarez, *T. rex and the Crater of Doom*, 76-81.
[90] Luis W. Alvarez, Walter Alvarez, Frank Asaro, and Helen V. Michel, *University of California Lawrence Berkeley Laboratory Report* LBL-9666 (1979).
[91] Luis Alvarez, *Alvarez: Adventures of a Physicist*, 258.
[92] Jan Smit and Jan Hertogen, "An extraterrestrial event at the Cretaceous-Tertiary boundary," *Nature* vol. 285, no. 5762 (May 22, 1980): 198-200.

Nature, geologist Kenneth J. Hsu speculated that the impact of a giant comet at the end of the Cretaceous would have created lethal acid rain.[93] Although the Smit and Hertogen paper was actually published before the Alvarez *Science* paper, the Alvarez team retained scientific priority because of their earlier announcements at the LBL Lab Report meeting and the AAAS meeting in San Francisco.

Other scientists of various disciplines were quick to contribute to the debate. In their original paper, the Alvarez team had found the iridium anomaly in three locations: Gubbio, Italy; Stevns Klint, Denmark; and (thanks to vertebrate paleontologist Dale A. Russell, who collected the samples and passed them on to the Alvarez team) Woodside Creek, New Zealand.[94] The Alvarez hypothesis predicted that anomalously high concentrations of iridium would be found at K-T boundary sections world-wide, and other scientists immediately set out to test this prediction.[95] Questions were also raised about the significance of the iridium anomaly: how frequently did such concentrations of iridium occur in the geological record, and could they result from other causes besides impact, such as diagenesis, biogenic concentration by marine microorganisms, or volcanic eruptions? A crucial paper in this period was published by geologist Carl Orth and colleagues.[96] Orth and his coworkers had discovered an iridium anomaly of K-T age, coincident with the palynologically defined K-T boundary[97], in coal beds of New Mexico. This was the first iridium anomaly found in terrestrially-deposited sediments, and its presence there proved that the iridium anomaly could not be an artifact of unusual marine deposition or biological concentration from seawater.[98]

While a number of papers established the rarity of iridium layers and showed that impact was the most likely cause, a small but vocal minority of scientists began to

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[93] Hsu, Kenneth J., "Terrestrial catastrophe caused by cometary impact at the end of the Cretaceous," *Nature* vol. 285, no. 5762 (May 22, 1980): 201-203.
[94] Walter Alvarez, *T. rex and the Crater of Doom*, 80.
[95] Luis W. Alvarez, Walter Alvarez, Frank Asaro, and Helen V. Michel, "Current status of the impact theory for the terminal Cretaceous extinction," in Leon T. Silver and Peter H. Schultz, eds., *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*. Geological Society of America Special Paper 190 (Boulder: The Geological Society of America, Inc., 1982), 305-315.
[96] Carl J. Orth, James S. Gilmore, Jere D. Knight, Charles L. Pillmore, Robert H. Tschudy, and James E. Fassett, "An iridium anomaly at the palynological Cretaceous-Tertiary boundary in northern New Mexico," *Science* vol. 214, no. 4527 (1981): 1341-1343.
[97] Palynology is the study of pollen. A palynologically defined K-T boundary is a boundary section which has been identified based on the pollen contained within the relevant rocks.

clamour for the volcanist hypothesis.[99] These scientists argued that all of the effects attributed by others to impact, including the iridium anomaly, world-wide dust cloud, acid rain, and global warming, could have been caused by the massive outpouring of the Deccan Traps, one of the largest eruptions of lava ever known, which was formed in what is now India at roughly the same time as the K-T boundary.[100] Likewise, some scientists began to search other mass extinction horizons for other iridium anomalies. Although several such anomalies were initially reported, after much discussion, only the K-T boundary and the Eocene-Oligocene boundary (approximately 35 million years ago) appeared to contain unequivocal iridium horizons.

A paper published in the May 25, 1984 issue of *Science* was widely regarded as providing the 'crucial experiment' or 'proof' of extraterrestrial impact.[101] Geologist Bruce F. Bohor and three colleagues, all with the United States Geological Survey, wrote that at a K-T boundary section in Montana, they had discovered shocked quartz: quartz crystals showing planar deformation structures formed during a burst of intense pressure.[102] Shocked quartz was only known to occur at impact sites and nuclear test

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[98] Walter Alvarez, *T. rex and the Crater of Doom*, 80-81.

[99] Alfred G. Fischer, "The two Phanerozoic supercycles," in W. A. Berggren and John A. Van Couvering, eds. *Catastrophes and Earth History: The New Uniformitarianism.* (Princeton: Princeton University Press, 1984), 129-150.

Kevin McCartney, Alan R. Huffman, and Marian Tredoux, "A paradigm for endogenous causation of mass extinctions," in Sharpton and Ward, eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*, 125-145.

Dewey M. McLean, "A terminal Mesozoic 'greenhouse': lessons from the past," *Science* vol. 201, no. 4354 (August 4, 1978): 401-406.

Charles B. Officer and Charles L. Drake, "The Cretaceous-Tertiary transition," *Science* vol. 219, no. 4591 (March 25, 1983): 1383-1390, and "Terminal Cretaceous environmental events," *Science* vol. 227, no. 4691 (March 8, 1985): 1161-1167.

Michael R. Rampino and Richard B. Stothers, "Flood basalt volcanism during the past 250 million years," *Science* vol. 241, no. 4866 (August 5, 1988): 663-668.

[100] Some of these volcanic models were even more complex, linking the eruptions to plate tectonics and convective currents in the Earth's mantle. McLean's model tied the volcanic outpouring to the cycling of carbon dioxide through the Earth's rocks, oceans, and atmosphere. See McLean's website at http://filebox.vt.edu/artsci/geology/mclean/Dinosaur_Volcano_Extinction/pages/ktec1981.html

[101] See for example:

Carlisle, *Dinosaurs, Diamonds, and Things from Outer Space*, 96.

Glen, "What the debates are about," 10.

Richard A. Kerr, "Huge impact is favored K-T boundary killer," *Science* vol. 242, no. 4880 (November 11, 1988), 865.

Ward, *The End of Evolution*, 139. Ward wrote that the evidence presented in the Bohor paper "seemingly removed most doubt about a 65-million-year-old meteor impact."

[102] Bruce F. Bohor, E. E. Foord, P. J. Modreski, and D. M. Triplehorn, "Mineralogical evidence for an impact event at the Cretaceous-Tertiary boundary," *Science* vol. 224, no. 4651 (May 25, 1984): 867-868.

sites, and had never been demonstrated to occur as the result of a volcanic eruption. Several scientists pointed out that as volcanic eruptions are not technically explosions, the pressures involved never reach any point higher than the pre-eruption mantle pressure, and are not sufficient to produce shocked quartz.[103] Although the volcanist camp, particularly Officer and Drake, tried to link the shocked quartz to volcanism, for most scientists, including paleontologists, the shocked quartz was seen as proof, or at least very strong evidence, of impact.[104] Even while such strong evidence was mounting for the impact itself, however, few scientists concerned themselves with the second part of the Alvarez hypothesis: the link between impact and extinction. Vertebrate paleontologists were almost alone in calling for the separation of proof of impact from link between impact and extinction, and did not agree that the impact had caused the mass extinction.

The Alvarez team was aware that their theory was not universally accepted, and that vertebrate paleontologists in particular did not support the impact extinction hypothesis. The various members of the Alvarez team responded to the vertebrate paleontologists and their dissent in various ways. Walter Alvarez, as a geologist, had a somewhat better understanding of and sympathy for the vertebrate paleontologists' arguments and reservations than did the rest of the team, who were all physical scientists.[105] An example of his attempts at conciliation between the physical and historical sciences was his article "Interdisciplinary aspects of research on impacts and mass extinctions; a personal view," published in the proceedings of the second Snowbird conference.[106] Alvarez identified seven barriers to crossing boundaries between scientific disciplines, including the problem of judging the validity of results in fields other than one's own, the difficulty of understanding the specialist jargon unique to each scientific discipline, and conflicts arising from the perceived hierarchy of sciences. Alvarez argued that the traditional hierarchy, with the physical sciences at the top and the historical and

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[103] See for example: Eugene Shoemaker, qtd. in Richard A. Kerr, "Huge impact is favored K-T boundary killer," *Science* vol. 242, no. 4880 (November 11, 1988), 866.
[104] Ryder, Fastovsky, and Gartner, "Preface," ix.
[105] Muller, *Nemesis, The Death Star*, 71.
[106] Walter Alvarez, "Interdisciplinary aspects of research on impacts and mass extinctions; a personal view," in Virgil L. Sharpton and Peter D. Ward, eds. *Global Catastrophes in Earth History: An*

social sciences at the bottom, does reflect real differences among scientific disciplines; however, he suggested that scientists should "drop the loaded terms like 'hierarchy' and 'pecking order' and simply arrange the sciences in a spectrum from mathematically sophisticated at one end to descriptively complex at the other."[107] The order Alvarez gave to his 'spectrum' ("mathematics, physics, chemistry, astronomy, geology, paleontology, biology, psychology, sociology"[108]) was the same as that of the hierarchy he sought to replace; the only difference between the 'spectrum' and the 'hierarchy', then, is that the former reflects "the kind of subject matter with which [different disciplines] deal", whereas the latter describes "the relative merits of the different sciences."[109]

In an expanded version of the same article published the following year in *GSA Today*[110], Alvarez concluded the section on the 'spectrum' of sciences with an example of how one aspect of the impact/mass extinction research would (or at least should) progress from the high to the low end of the 'spectrum'. In this example, Alvarez described how chemists might detect precise quantities of iridium in boundary rocks, which geologists must then evaluate to determine how, and how fast, the iridium was deposited. Next, paleontologists must define the K-T mass extinction and decide if the iridium anomaly occurred at the same time as the extinctions, taking into account such factors as bioturbation and sampling artifacts. Then, "if the evidence for impact seems to coincide with the extinction level," paleobiologists and paleoecologists must "consider what the geographical extinction pattern was, what were the lifestyles of victims and survivors, and which of the suggested killing mechanisms… might have affected each group."[111] Finally, evolutionary biologists must re-examine the foundations of evolutionary thought in the light of the conclusions reached in this line of investigation.

Alvarez's procedure for moving the line of inquiry through the scientific 'spectrum' looks very good on paper, but in practice, the impact/mass extinction debate

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Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality. Geological Society of America Special Paper 247. (Boulder: The Geological Society of America, Inc., 1990), 93-97.
[107] *Ibid.*, 95.
[108] *Ibid.*
[109] *Ibid.*
[110] Walter Alvarez, "The gentle art of scientific trespassing," *GSA Today* vol. 1, no. 2 (February 1991): 29-31, 34.

did not function this way. There is a major flaw in this example as Alvarez described it. What Alvarez has written is an idealized scenario in which, at each stage of inquiry, the support for extinction-by-impact grows. At each stage, the relevant group of scientists accepts the evidence and judgment handed to them by the group before, evaluates the evidence according to the procedures and standards of their own discipline, finds that their evaluation has also supported the impact theory, and hands the problem off to the next level. William Glen's observations of the impact debate led him to conclude that "subscription to the same conflicted hypothesis… conditions the cognition of facts, methods, standards of appraisal, and much more, such as to foster commensurable views even among those from unrelated disciplines."[112] Glen's conclusions are supported by the evidence here; Alvarez's model does indeed appear to work if all of the scientists involved support the same hypothesis. But what happens when scientists from a 'lower' discipline find that their evidence does not give the same answer as that found by scientists from 'higher' up? What if scientists from different disciplines think that other evidence is equally or more important? And what if scientists of different disciplines want to ask totally different questions?

In reality, as the various lines of evidence in the impact debate passed down from the physical sciences to the historical sciences, vertebrate paleontologists agreed with some of the conclusions made by those 'above' them, such as: there was an iridium anomaly, it did not appear to have been formed by biogenic, sedimentary, or volcanic processes, and it did appear to have been formed during a bolide impact. These conclusions were – quite properly – made by the physical and geological scientists most competent to evaluate the relevant geochemical and geophysical evidence, and most vertebrate paleontologists did not question them.

However, when it came to evaluating their own evidence, vertebrate paleontologists did not find unequivocal evidence that a bolide impact had caused the K-T mass extinction. Vertebrate paleontologists rejected the impact hypothesis as the (sole) extinction mechanism[113]… but their conclusions were not accepted by those higher up on

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[111] *Ibid.*, 31.
[112] Glen, "A manifold current upheaval in science," 204.
[113] For reasons which will be described in Chapters 3 and 4.

the scientific 'spectrum'. Thus we see that, for all Alvarez's soothing reassurances, the scientific 'spectrum' is still really a 'hierarchy'. Many physical scientists who supported the impact hypothesis – in particular, Luis Alvarez himself – did not want to believe the contradictory conclusions reached by the vertebrate paleontologists, so they simply chose to disbelieve them. Their grounds for disbelieving these conclusions – that 'paleontologists aren't very good scientists'[114], that 'they don't understand statistics'[115], or that 'they just can't admit it when the evidence proves they're wrong'[116] – really come back to the idea of the scientific hierarchy. Luis Alvarez in particular, and other physical scientists as well, believed that the methods of physical science are better than those of the historical sciences, and physical scientists are the ultimate judges of truth, not the historical scientists. It was these beliefs that allowed some physical scientists to disbelieve or dismiss the conclusions reached by vertebrate paleontologists.[117]

Walter Alvarez concluded (in both papers) that the best way to cross disciplinary boundaries is for scientists to learn the language of the discipline they wish to enter, which will provide them not only with the tools for understanding the new discipline, but the respect and acceptance of the discipline's members. Alvarez stated:

> The key to judging research results across disciplines thus comes down to rigorous care and full explanation on the part of the producer, and the willingness of the reader to delve deeply into an unfamiliar literature.[118]

Again, Alvarez's recommended procedure might work in theory but was not applied in practice: neither he nor his father 'delved deeply' enough into the literature of paleontology to understand the objections made by vertebrate paleontologists. In an article published in the *Proceedings of the National Academy of Sciences*, Luis Alvarez

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[114] Luis Alvarez qtd. in Malcolm W. Browne, "The debate over dinosaur extinction takes an unusually rancorous turn," *New York Times* (January 19, 1988), C4.
[115] Jastrow, "The dinosaur massacre: a double-barreled mystery," 52.
[116] Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 629.
[117] Elisabeth S. Clemens, "The impact hypothesis and popular science: conditions and consequences of interdisciplinary debate," in William Glen, ed. *The Mass-Extinction Debates: How Science Works in a Crisis* (Stanford: Stanford University Press, 1994),111. Clemens stated that a combination of their higher status and their better coverage by the press allowed physical scientists to "dismiss the specialized training of others."
[118] Walter Alvarez, "Interdisciplinary aspects of research on impacts and mass extinctions," 96.
Walter Alvarez, "The gentle art of scientific trespassing," 34.

presented his evidence that the Alvarez team had "all thought deeply about all phases of the subject"; this evidence consisted of him and team member Helen Michel each going out to collect rocks, and an episode in which Michel's husband tripped over a *Triceratops* skull.[119] It is doubtful that any vertebrate paleontologists thought either of these examples qualified the Alvarez team to pass judgment on paleontological evidence.

The 'depths' reached by Walter Alvarez in attempting to understand the arguments of vertebrate paleontology can be estimated by taking a closer look at his example of a line of evidence moving through the scientific hierarchy. When Alvarez described the procedures paleontologists must employ when the evidence comes to them, he acknowledged that they must determine whether apparent extinction rates are real or reflect sampling artifacts, which is a genuine investigation of the paleontological evidence. However, Alvarez implied that the ultimate question for the paleontologists is "whether the Ir [=iridium] input coincided in time with a mass extinction." Alvarez continued:

> If the evidence for impact seems to coincide with the extinction level, paleoecologists... have to consider what the geographical extinction pattern was, what were the life styles of victims and survivors, and which of the suggested killing mechanisms – darkness, acid rain, greenhouse heating, fires, etc... – might have affected each group.

In Alvarez's interpretation, then, the paleontologists' questions were: 'Did the iridium layer coincide with the mass extinction?', and 'Which specific impact kill mechanisms killed which specific creatures?' In reality, vertebrate paleontologists were asking very different questions. The first problem with Alvarez's questions is that the causal link between impact and extinction is not directly addressed, but is assumed to be proved if a temporal coincidence between the two events is established. Vertebrate paleontologists did not accept that temporal coincidence alone proves cause and effect, and, as we shall see in later chapters, they also argued that in fact the impact did not coincide with many of the extinctions. The second problem is that, in Alvarez's interpretation, the impact is assumed to be the extinction cause and it only remains to sort particular victims according to their particular kill mechanisms. Alvarez has failed to

[119] Luis W. Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 627. This quotation is discussed in more detail in Chapter 4.

recognize an entirely separate line of paleontological inquiry: 'What are the possible, testable causes that have been proposed to explain the K-T mass extinction?' 'Which of these causes is/are most supported by the available fossil evidence, including the physiologies of both victims and survivors?' 'How do the K-T extinctions compare to other mass extinctions in Earth history, and can these mass extinctions be explained by the same cause(s)?' This evidence shows that the greatest incommensurability between the Alvarez team and the vertebrate paleontologists was the difference in the questions they wanted to ask, and the questions they thought had already been answered. These questions will be discussed in more detail in Chapter 4.

Walter Alvarez was aware of the difficulties in communicating across disciplinary boundaries and tried to minimize them by writing the articles discussed above, although his efforts were unsuccessful. His father, on the other hand, made no such conciliatory attempts. Luis Alvarez was extremely frustrated by vertebrate paleontologists' reluctance to embrace the impact hypothesis, and made several disparaging comments which only served to further alienate the paleontological community. For example, in a 1988 interview with Malcolm W. Browne of the *New York Times*, Alvarez paraphrased Ernest Rutherford's famous remark with the following statement: "I don't like to say bad things about paleontologists, but they're really not very good scientists. They're more like stamp collectors."[120] Alvarez also impugned the work of vertebrate paleontologist William A. Clemens, a colleague at Berkeley and one of the impact theory's most vocal opponents. Alvarez said "that he considers Dr. Clemens inept at interpreting sedimentary rock strata and that his criticisms can be dismissed on grounds of general incompetence."[121]

Some of Alvarez's belligerence can be attributed to his personal situation and motivations. He was already retired – although still working – when the Berkeley team's impact research began, and he turned sixty-nine the week after the 1980 *Science* article was published. Alvarez's friend and former student Richard Muller described in his 1988

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[120] Luis Alvarez qtd. in Browne, "The debate over dinosaur extinctions takes an unusually rancorous turn," C4.
[121] *Ibid.*, C4.

book how Alvarez was extremely upset that the impact theory was not accepted by many paleontologists, which at first Muller did not understand. Muller continued:

> Then I realized that most of the paleontologists who disputed Luie's discovery would outlive him. Luie was over seventy years old. I could afford to be patient, but Luie couldn't, not if he was going to see his theory become part of the standard dogma.[122]

In 1987, Alvarez was diagnosed with terminal cancer of the esophagus.[123] His interview with the *New York Times*, which included his comments about William Clemens in particular and paleontologists in general, was made after this diagnosis. In the same interview, Alvarez stated: "I can say these things about some of our opponents because this is my last hurrah, and I have to tell the truth." Alvarez's frustration with vertebrate paleontologists' inability to understand and accept 'the truth', however, were also expressed in earlier publications. This frustration did not just arise out of a desire to witness the universal acceptance of the impact theory during his lifetime, but stemmed more from Alvarez's tendency to see things in absolute terms (as evidenced by the Oppenheimer incident recounted earlier in this chapter), and his inability to understand how anyone could be presented with the same data and not draw from them the same conclusion as he did.

For Luis Alvarez in particular, and impact supporters in general, the mystery of the extinction of the dinosaurs had been solved.[124] The iridium anomaly and other physical and geochemical evidence amassed by the multitude of geologists and physical scientists involved in the debate had proved, to nearly universal satisfaction, that an impact had taken place. Given that an impact had occurred, its connection to the K-T mass extinction was obvious, almost beyond question. After all, it was the mass extinction at the level of the mysterious clay layer which had led to the discovery of the impact in the first place; and it was ludicrous to imagine that a devastating bolide impact and one of the greatest mass extinctions of all time could have occurred at the same time coincidentally. Alvarez expected that other scientists would evaluate the evidence for

[122] Muller, *Nemesis, The Death Star*, 73-74.
[123] Powell, *Night Comes to the Cretaceous*, 164.
[124] Luis Alvarez, *Alvarez: Adventures of a Physicist*, 257.

impact and immediately embrace the impact hypothesis[125] – and indeed, many scientists did. So why couldn't the vertebrate paleontologists accept that the impact had caused the mass extinction? In frustration, Luis Alvarez could only conclude that paleontologists were not good scientists. The vertebrate paleontologists, on the other hand, felt that they had several very good reasons for doubting the impact was the (sole) cause of the mass extinctions. These reasons, and the attempts made by vertebrate paleontologists to articulate them, form the basis of the next two chapters.

[125] Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 629.

Chapter 3: Vertebrate Paleontologists in the Impact Debate

As we saw in Chapter 2, the Alvarez impact hypothesis was supported by many geophysical, geochemical, and lunar/planetary scientists, who immediately set out to model the effects of a bolide impact on the Earth. Those scientists whose work focused on the biological implications of such an impact – in particular, vertebrate paleontologists – remained skeptical, not necessarily of the impact itself, but of its supposed connection to the K-T mass extinction. Chapter 3 documents the degree to which vertebrate paleontologists participated in the impact/mass extinction debate, and also explores the nature of this participation. First I offer a brief analysis of relevant articles published in *Science*, to contrast the publications of vertebrate paleontologists with those of other scientists. Next, I present a chronological narrative of vertebrate paleontologists' contributions to the debate, and elucidate some of their methods, standards of evidence, and objections to the Alvarez theory. This chapter concludes with a comparison of several polls conducted over the past twenty years, including one done by the author. These polls each document the status of the impact hypothesis within the vertebrate paleontology community at a particular moment in time; taken together they show how the response of vertebrate paleontologists to the impact theory and its proponents has evolved over time.

The rejection of the Alvarez impact hypothesis by the vertebrate paleontology community was made apparent very early on in the impact debate. In a *Science* editorial dated October 31, 1980, Richard A. Kerr summarized the mounting evidence for a bolide impact but conceded that its connection to the K-T mass extinction remained tenuous, at least in the minds of paleontologists:

> Whether dust thrown up by the impact of an asteroid led to the extinctions that occurred near the Cretaceous-Tertiary boundary is much less certain than the existence of the asteroid. ... While admitting a certain cultural bias against catastrophic causes for extinctions, many paleontologists firmly believe that the pattern of extinction, what survived and what did not, does not jibe with that expected to result from 2 or 3 years of darkness.[126]

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[126] Richard A. Kerr, "Asteroid theory of extinctions strengthened," *Science* vol. 210, no. 4469 (October 31, 1980): 516-517.

Kerr also discussed the differing views among terrestrial (vertebrate) and marine (invertebrate) paleontologists, with regard to the impact hypothesis:

> Terrestrial paleontologists do not see the match between the Berkeley scenario and the fossil record as being as good on land as in the ocean. ... The strongest evidence for instantaneous extinctions remains the marine microfossils.[127]

As discussed in the Introduction and Chapter 1, the 1980 Alvarez article that spawned the impact/mass extinction debate was published in the June 6, 1980, issue of the weekly magazine *Science*. This multi-disciplinary journal has been identified by some actors in the K-T impact/mass extinction debate as the principle forum of publication in which the debate has been played out – or at least the principle forum of publication for *supporters* of the Alvarez hypothesis.[128] Analysis of a bibliography of the "Cretaceous-Tertiary boundary event" published in 1992 shows that of 684 references, 101 refer to articles, editorials, or letters published in *Science*. This number is just under fifteen percent of the total, a significant proportion.[129]

I conducted an independent and more inclusive analysis of *Science*, in which I noted all sources discussing any aspect of the Cretaceous-Tertiary mass extinction; any other mass extinction event or impact event which is compared to or contrasted with the K-T event; and articles on periodic extinctions and/or impacts in which the K-T extinction or impact is discussed as part of the cycle.[130] This analysis showed 222 relevant articles, editorials, and letters between the 1980 Alvarez paper and the end of 2002.

These 222 pieces were written by 335 authors and co-authors, only 28 of whom (8.36%) can be identified as vertebrate paleontologists (Figure 2). These 28 vertebrate paleontologists wrote or co-wrote 28 of the 222 articles, or a mere 12.6%. By

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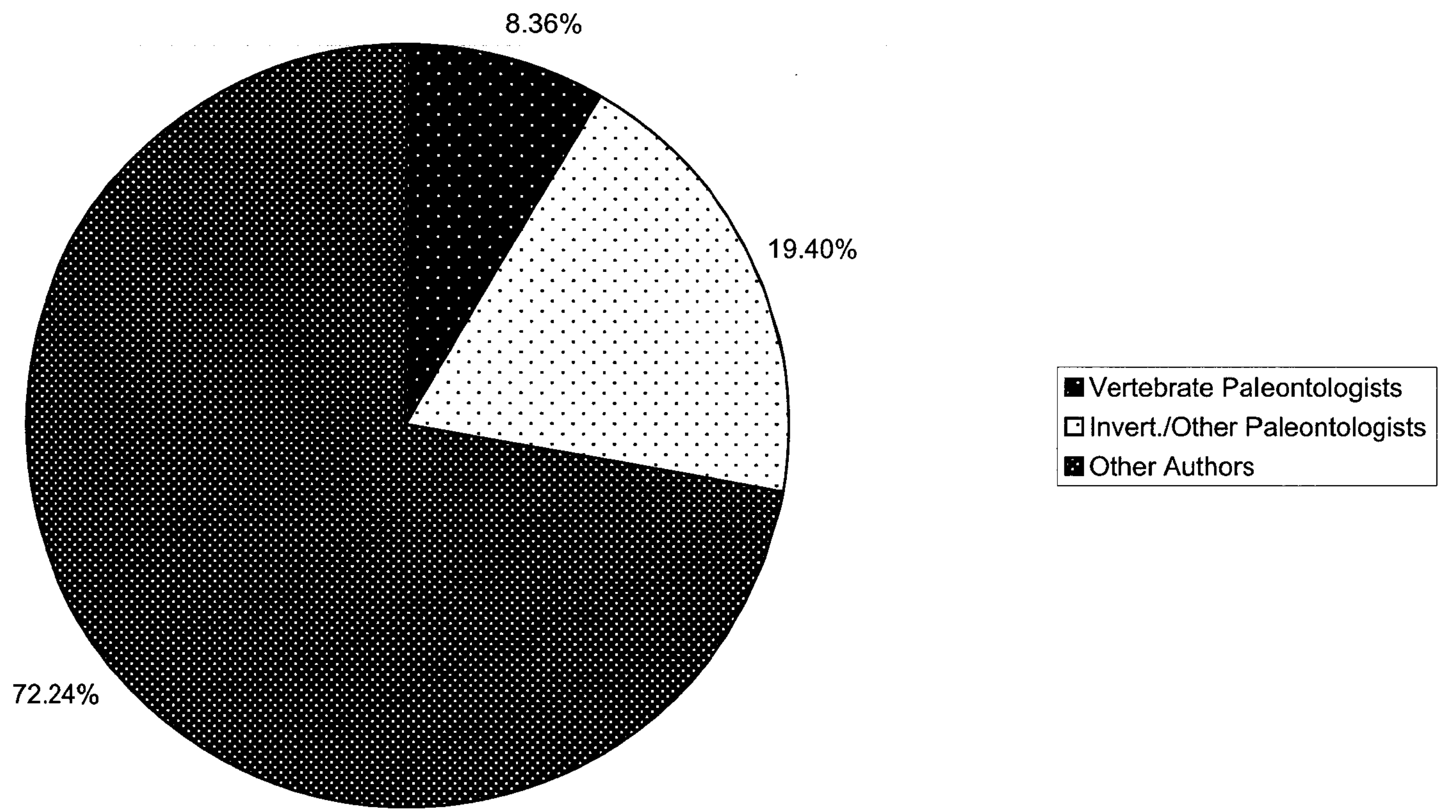
[127] Richard A. Kerr, "Asteroid theory of extinctions strengthened," *Science* vol. 210, no. 4469 (October 31, 1980), 516.
[128] Officer and Page, *The Great Dinosaur Extinction Controversy*, 96-97.
Benton, "Scientific methodologies in collision," 393. Benton wrote: "most of the debate has been carried on so far in the pages of *Science* and *Nature*."
[129] Timothy T. Tokaryk, J. E. Storer, and E. M. V. Nambudiri, *Selected Bibliography of the Cretaceous-Tertiary Boundary Event, Through 1989*. Natural History Contributions No. 11, Saskatchewan Museum of Natural History (Regina: Government of Saskatchewan, 1992).

Figure 2. (Co-) Authors of *Science* Articles, by Discipline (n=335)



comparison, 65 authors are invertebrate paleontologists, ichnologists, or paleobotanists, and these 65 authors wrote or co-wrote 58 articles, or 26.1% of the total. Finally, 242 authors are from other scientific fields ranging from geology to chemistry to physics to astronomy. Four editorialists for *Science* are also included among these 242 'other authors', who wrote the remaining 148 or 66.7% of articles.[131]

These figures clearly demonstrate two points: first, that the weekly magazine *Science* was a principal forum for publication on matters relevant to the impact/mass extinction debate; and second, that vertebrate paleontologists comprised only a small proportion (8.36%) of the authors publishing on the subject (at least in this magazine). A brief examination of the *Journal of Vertebrate Paleontology* and *Paleobiology*, two of the principal paleontological journals, over the same time frame (1980 to 2002) shows that only 8 and 5 articles were published respectively relevant to the debate, which supports the contention that vertebrate paleontologists did not participate in the impact debate to any great extent.[132]

Although the majority of vertebrate paleontologists did not participate in the impact/mass extinction debate, a select few did attend the various conferences convened on the subject, and/or published several papers on the cause of the K-T mass extinction. In this chapter I will explore the published reactions of vertebrate paleontologists to the Alvarez impact hypothesis and elucidate their main arguments. It will be necessary also to briefly mention the contributions of some scientists of other disciplines, in order to address the responses made by vertebrate paleontologists to the arguments and theories of these other scientists. I will place a particular emphasis on the work of dinosaur

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[130] See Appendix A. I did not count articles that discussed bolides or non-terrestrial craters without linking them to extinction episodes, nor did I include paleobiological or paleoecological articles that discussed end-Cretaceous species without reference to the extinction event.

[131] The total number of articles for vertebrate paleontologists, invertebrate paleontologists, and other authors add up to more than the total number of articles because twelve articles included both vertebrate and other paleontologists as authors and were therefore counted twice. In passing, it is interesting that vertebrate and invertebrate/other paleontologists only co-wrote twelve of their combined total of 74 articles (only 16.2%). This minimal overlap in authorship supports the statements made by several authors regarding the fundamental practical and theoretical split between vertebrate and other paleontologists. See for example: Glen, "How science works in the debates," 52.

[132] These articles in the *Journal of Vertebrate Paleontology* and *Paleobiology* are listed in the main bibliography.

paleontologist Dale A. Russell, and mammal paleontologist William A. Clemens, the most active participants in the impact debate among vertebrate paleontologists.

Dale A. Russell has been identified by several players in the impact/mass extinction debate, including other vertebrate paleontologists, as the only vertebrate paleontologist to immediately embrace the Alvarez impact hypothesis, and the only one to argue for catastrophic dinosaur extinction.[133] From an examination of Russell's published work, and by his own admission, it can be seen that his favorable reception of Alvarez theory stemmed largely from a prior theoretical commitment, which in turn grew out of Russell's unique work on and perception of dinosaur biology.

Russell was born in San Francisco, California, on December 27, 1937. He obtained a B.A. in biological sciences from the University of Oregon in 1958, and completed his M.A. in paleontology at the University of California at Berkeley in 1960, under the supervision of paleontologist Donald Savage. This is the same institution at which the Alvarez team would later be based, and Luis Alvarez was already working at the university's Lawrence Berkeley Laboratory by that time. Russell completed a Ph.D. in geology at Columbia University in 1964, under the supervision of dinosaur paleontologist Edwin H. Colbert. From 1965 to 1995, Russell worked at the Museum of Nature, National Museum of Canada, in Ottawa, first as the chief of the museum's Paleobiology Division, then (from 1977 on) as the Curator of Fossil Vertebrates.[134] Since

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[133] The following sources identify Russell as the most prominent, if not the only, supporter of catastrophic dinosaur extinction among vertebrate paleontologists:
Walter Alvarez, *T. rex and the Crater of Doom*, 58.
Archibald, *Dinosaur Extinction and the End of an Era*, 33.
Robert T. Bakker, *The Dinosaur Heresies: New Theories Unlocking the Mystery of the Dinosaurs and Their Extinction* (New York: Zebra Books, 1986), 435.
Ward, *The End of Evolution*, 118.
In the following article, Russell actually *apologizes* for holding a catastrophic view of dinosaur extinction, indicating that this opinion is not only unusual but unappreciated:
Dale A. Russell, "Terminal Cretaceous extinctions of large reptiles," 373-384, in Berggren and Van Couvering, eds. *Catastrophes and Earth History: The New Uniformitarianism*, 373.
[134] Pamela M. Kalte and Katharine H. Nemeh, "Russell, Dale A.," *American Men and Women of Science*, 21st ed. vol. 6 (Detroit: The Gale Group, 2003), 389.
North Carolina State Museum Website
<http://www.naturalsciences.org/research/paleontology/russell.html>

1995, Russell has been working at the North Carolina State Museum of Natural Sciences and North Carolina State University.[135]

Although Russell worked on mammals for his master's thesis and mosasaurs for his doctoral dissertation, he was also interested in dinosaur systematics, intelligence, and extinction, which he has examined for much of his career. Russell first became interested in the K-T boundary in 1964 or 1965, shortly after he came to Canada. One of Russell's major contributions around this time was a monograph detailing dinosaur diversity in Western North America during late Cretaceous time, published in 1967.[136] Russell realized in compiling this survey that dinosaur diversity had not declined through the late Cretaceous as so many people thought; if one corrected for sample size and was careful to compare equal units of time, dinosaur diversity at the family level in fact remained constant or even increased towards the K-T boundary.

At the same time, Russell was also developing a unique perspective on evolution in general, and the evolution of intelligence in particular. In the 1960s, he came across the skull of a *Troodon*, a small theropod dinosaur also known as *Stenonychosaurus*,[137] in the American Museum of Natural History. Russell noticed that it seemed to have a very large brain for a dinosaur, and wondered why no one had noticed this before. He set out to find more *Troodon* fossils, and eventually located some remains in the Oldman Formation of Dinosaur Provincial Park, Alberta. In his 1969 paper describing this find, Russell showed that *Troodon* is the most intelligent dinosaur yet known, with an encephalization quotient (EQ) or brain-to-body-size ratio approaching those of birds and primitive mammals.[138] Russell began to suspect that in *Troodon*, the dinosaurs had begun to evolve towards increased intelligence, and wondered how intelligent *Troodon*'s descendants might have become if they had not suddenly become extinct. In addition, Russell noticed that *Troodon* was bipedal, with large, forward-looking eyes, and three-fingered hands with versatile and opposable digits. Russell was fascinated to think that

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[135] North Carolina State Museum Website, <http://www.naturalsciences.org/research/paleontology/russell.html>, viewed July 24, 2003.
[136] Dale A. Russell, *A Census of Dinosaur Specimens Collected in Western Canada* (National Museum of Canada Natural History Papers No. 36, Ottawa, 1967).
[137] *Stenonychosaurus* is now considered to be an invalid synonym of *Troodon*.
[138] Dale A. Russell, "A new specimen of *Stenonychosaurus* from the Oldman Formation (Cretaceous) of Alberta," *Canadian Journal of Earth Sciences* vol. 6 (1969): 595-612.

this small dinosaur looked more human than the tiny, quadrupedal mammals scurrying around at the same time which were our true ancestors.

This interest in dinosaur intelligence led Russell to write several papers on the subject of extraterrestrial intelligence, and eventually culminated in Russell's best-known work: his model of a dinosauroid (Plate 3).[139] The question of where intelligent dinosaurs might have ended up had they not suffered an untimely demise continued to intrigue Russell, to the extent that in 1982 he collaborated with artist and taxidermist Ron Seguin to create what they called a dinosauroid.[140] The dinosauroid projected *Troodon*'s high EQ into a possible evolutionary future in which dinosaur intelligence is comparable to our own. The dinosauroid is a fully upright, bipedal figure, with a rounded, relatively humanoid skull, and human-like although three-fingered hands.

Russell's view of the potential for dinosaur intelligence, coupled with his work showing no decline in dinosaur diversity through the end of the Cretaceous, gave him a unique view of the dinosaurs' extinction. Russell believed that the evolution of intelligence had been delayed by millions of years with the extinction of the dinosaurs,[141] and this belief necessarily required a positive view of the dinosaurs' potential for evolutionary success.

Dinosaur paleontologists had already begun to suspect, from the hot-blooded/cold-blooded debate of the 1970s, that at least some dinosaurs were not stupid, sluggish reptiles, but metabolically active, rapidly growing, successful predators.[142] Although the idea of endothermy in dinosaurs challenged the idea of dinosaurs as racially senile evolutionary dead ends on some levels, the paradigm of gradual dinosaur decline prevented most paleontologists from seriously challenging the orthodox view of dinosaur evolution and extinction. Russell, however, stood alone among vertebrate paleontologists

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[139] Dale A. Russell, "Exponential evolution: implications for intelligent extraterrestrial life," *Advances in Space Research* vol. 3 (1983): 95-103.
Dale A. Russell, "Biodiversity and time scales for the evolution of extraterrestrial intelligence," *Astronomical Society of the Pacific, Conference Series* vol. 74 (1995): 143-151.
Dale A. Russell and Ron Seguin, "Reconstruction of the small Cretaceous theropod *Stenonychosaurus inequalis* and a hypothetical dinosauroid," *Syllogeus* vol. 37 (1982).
[140] Russell and Seguin, "Reconstruction of the small Cretaceous theropod," 43.
[141] Dale A. Russell, "The mass extinctions of the late Mesozoic," *Scientific American* vol. 246, no. 1 (January 1982), 65.
Muller, *Nemesis, The Death Star*, 77.
[142] Spalding, *Into the Dinosaurs' Graveyard*, 137.

Plate 3. Reconstructions of *Troodon* (=*Stenonychosaurus*) and a Hypothetical Dinosauroid

This photograph shows two models built by Dale A. Russell and Ron Seguin. In the background is *Troodon* (=*Stenonychosaurus*), a theropod or meat-eating dinosaur, and the most intelligent dinosaur known to date. Note *Troodon*'s bipedal posture, large, forward-facing eyes, and agile-looking hands with one digit opposable to the other two.

In the foreground is the hypothetical dinosauroid, a projection of the intelligent creature *Troodon* might have evolved into if it had not gone extinct at the end of the Cretaceous period, along with all the other (non-avian) dinosaurs. Note the dinosauroid's upright stance, large cranium, and human-like (although three-fingered) hands.

Source: Dale A. Russell and R. Seguin. *Reconstructions of the Small Cretaceous Theropod* Stenonychosaurus inequalis *and a Hypothetical Dinosauroid* Syllogeus no. 37 Ottawa: National Museums of Canada, 1982.

in believing that the dinosaurs had not declined gradually for several million years, but had instead vanished abruptly, and at a time when they appeared to be otherwise successful in evolutionary terms. Because of his belief that the dinosaurs disappeared suddenly and mysteriously, and at a time when they were evolutionarily poised to begin developing an avian, if not simian, level of intelligence, Russell was willing to embrace a catastrophic, extraterrestrial explanation for their extinction.

Russell joined forces with physicist Wallace Tucker, and through the 1970s published several papers advocating the supernova hypothesis for dinosaur extinction.[143] The supernova hypothesis was also advocated by physicist Malvin A. Ruderman, a friend of Luis Alvarez's, who worked at the Los Alamos Laboratory in New Mexico. Russell gave a talk in 1978 at the NASA Ames Laboratory on the supernova hypothesis. The Alvarez team also attended, to present their work on the iridium anomaly at Gubbio. When Asaro and Michel thought they had found plutonium-244 in the clay samples from Gubbio, Walter Alvarez telephoned Dale Russell to let him know they had found evidence supporting the supernova hypothesis. This was the beginning of a period of scientific collaboration between Russell and the Alvarez team. The collaboration was mutually beneficial. Russell had been unable to convince his paleontological colleagues to take his notions of catastrophic dinosaur extinction seriously, and had not been successful in his efforts to recruit assistance in looking for extraterrestrial markers at the K-T boundary.[144] Now, finally, someone was taking a look. The Alvarez team perhaps benefited even more from Russell's support. He was one of the only paleontologists – certainly the only vertebrate paleontologist – willing even to listen to what they had to say. When Walter Alvarez informed Russell that the supernova hypothesis had been ruled out and they were now considering an asteroid impact, Russell accepted the new theory eagerly.[145] It explained the geochemical evidence better than the supernova

[143] See for example:
Russell and Tucker, "Supernovae and the extinction of the dinosaurs," 553-554.
Dale A. Russell, "The disappearance of the dinosaurs," *Canadian Geographical Journal* vol. 83 (1971): 204-215.
Dale A. Russell, "The enigma of the extinction of the dinosaurs," *Annual Review of Earth and Planetary Sciences*, vol. 7 (1979): 163-182.
[144] Walter Alvarez, *T. rex and the Crater of Doom*, 58.
[145] William Glen, interview with Dale A. Russell, *Project in the History of the Mass-Extinction Debates: Oral History Interviews, 1984-1994* (June 29, 1984).

hypothesis, but like the supernova hypothesis, it invoked a sudden and unusual cause for the dinosaur extinction, which fit with Russell's interpretation of the dinosaur fossil record.

The Alvarez team arranged the necessary funding for Russell to give a talk about the catastrophic extinction of the dinosaurs at the January 1980 AAAS meeting in San Francisco – the same meeting at which they announced their impact hypothesis. As mentioned in Chapter 2, Russell sent the Alvarez team some K-T boundary samples he had collected in New Zealand, which also proved to contain an iridium anomaly, and Russell spent a year's sabbatical at Berkeley in 1982/1983 to continue working on the impact/mass extinction hypothesis.[146]

At Berkeley, Russell and the Alvarez team began a series of weekly meetings to discuss the evidence for the impact/mass extinction hypothesis.[147] The meetings were held with William A. Clemens of Berkeley's paleontology department, who has been identified as the impact theory's most vocal opponent among vertebrate paleontologists.[148]

Clemens was born in Berkeley, California, on May 15, 1932. He received his B.A. in 1954, and his Ph.D. in paleontology in 1960, both from the University of California at Berkeley. Clemens worked as a professor and Curator of Fossil Higher Vertebrates at the University of Kansas from 1961 to 1967, then moved to a professorship in the paleontology department of Berkeley, where he remained until his retirement in 2003.[149] Although principally a mammalogist, Clemens's interest in the K-T transition required him to become something of a dinosaur expert as well. Clemens spent the majority of his career studying the latest Cretaceous and earliest Tertiary

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[146] Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 637. Alvarez writes that Russell "is on sabbatical leave at Berkeley". Since this article was submitted October 12, 1982, I conclude that Dr. Russell spent the academic year 1982/1983 at Berkeley.
[147] Lowell Dingus and Timothy Rowe, *The Mistaken Extinction: Dinosaur Evolution and the Origin of Birds* (New York: W. H. Freeman and Company, 1998), 50.
[148] See for example:
Walter Alvarez, *T. rex and the Crater of Doom*, 86.
William Glen, "Introduction," in Glen, ed., *The Mass-Extinction Debates*, 6.
Muller, *Nemesis, The Death Star*, 76.
[149] Kalte and Nemeh, "Clemens, William Alvin," *American Men and Women of Science* vol. 2, 285.

vertebrate fauna of the Hell Creek Formation in Montana. This is the only section preserving a record of the terrestrial fauna across the K-T boundary which has been studied in any depth, anywhere in the world.[150]

According to Clemens's own recollection, his first objection to the Alvarez hypothesis was to the structure of their 1980 *Science* paper.[151] The Alvarez team conflated what Clemens saw to be, and what are now generally recognized as, two distinct hypotheses: one, that a bolide impact had occurred at the end of the Cretaceous period, and two, that this bolide impact was the sole or primary cause of the K-T mass

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Dr. Clemens's retirement was announced in an email posted to the VRTPALEO Listserver by Dr. D. Polly on February 16, 2003.

[150] The rocks of the Cretaceous Hell Creek Formation and the overlying Tertiary Tullock Formation in Montana preserve the fossils of dinosaurs and other vertebrates in the remains of several channels from a fluvial or river system of the latest Cretaceous and earliest Tertiary periods. (I will refer to this area as Hell Creek for simplicity, and because that is how most geologists and paleontologists refer to it.) Dingus and Rowe (*The Mistaken Extinction*) stated that there are only three locations known anywhere in the world which both yield dinosaur fossils and span the K-T boundary. Of these three locales, Hell Creek is the only one which has been studied in detail. (p. 82). Despite the fact that it has been studied by several scientists (including William Clemens) for decades, the succession of rock strata at Hell Creek remains difficult to interpret, because it is made up of younger channels cutting down into and reworking older sediments and fossils, so that it is very difficult – in some places impossible – to determine the relative ages of the fossils found there. Some scientists claim to have found dinosaurs of Tertiary age at Hell Creek, but so far these reports have been dismissed as Cretaceous fossils reworked into Tertiary channels (see J. David Archibald and Laurie J. Bryant, "Differential Cretaceous/Tertiary extinctions of nonmarine vertebrates; evidence from northeastern Montana," in Sharpton and Ward, eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*, 559.) The K-T boundary at Hell Creek is usually defined by a coal seam known as the "Z coal", and for many years no dinosaur remains were found closer to the boundary than 3 metres below the coal: this is the infamous "Three-metre gap" (or "the Ten-foot gap", to the Americans). The appropriateness of conflating the K-T boundary with the level of the Z coal is a contested issue; Archibald and Clemens admitted in 1982 that the Z coal could not be traced across outcrops, and that dinosaur fossils sometimes occurred above as well as below the coal (J. David Archibald and William A. Clemens, "Late Cretaceous extinctions," *American Scientist* vol. 70, no. 4 (July-August 1982), 379-380.) The interpretation and significance of the gap itself has also received a great deal of scientific scrutiny. Sheehan et al (Peter M. Sheehan, David E. Fastovsky, Raymond G. Hoffman, Claudia B. Berghaus, and Diane L. Gabriel, "Sudden extinction of the dinosaurs: Latest Cretaceous, Upper Great Plains, U.S.A.," *Science* vol. 254, no. 5033 (November 8, 1991): 835-839) conducted a systematic search for dinosaur remains and narrowed the gap to 60 centimetres. Williams ("Catastrophic versus noncatastrophic extinction of the dinosaurs," 183-190) pointed out, however, that closing the gap and filling the gap are not the same thing, and even if one or two dinosaur fossils are eventually found right at the K-T boundary, scientists will still have to explain why the fossils become less abundant as one approaches the K-T boundary (p. 187). See also Luis Alvarez's dismissal of the gap as statistically insignificant (Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 627-642), and Dale A. Russell, Letter, ("The gradual decline of the dinosaurs – fact or fallacy?") *Nature* vol. 307 (January 26, 1984): 360-361.
Also note Archibald's criticisms that Russell's statistics are based on faulty assumptions and are therefore invalid (Archibald, *Dinosaur Extinction and the End of an Era*, 33-47).

[151] William Clemens, "On the mass-extinction debates: an interview with William A. Clemens, conducted and compiled by William Glen," 239-240.

extinction. The majority of the fourteen-page Alvarez paper was taken up with their discussion of the evidence for an impact proper, while they devoted only two thirds of one page to the predicted biological effects of the hypothetical impact, and did not discuss the known fossil record at all. Clemens was disturbed by the fact that "Circumstantial evidence, apparent synchrony of impact and extinctions, was the only link between the two hypotheses."[152] What made things more disturbing to Clemens was that while the impact may have been synchronous with some or many marine invertebrate extinctions, his own experience with the K-T boundary section at Hell Creek led him to believe that the impact was not synchronous with the extinction of the dinosaurs, who seemed to have disappeared two to three metres below the iridium horizon.[153]

The interest in the impact/mass extinction hypothesis among scientists in general was such that several conferences were convened dealing solely with this topic and its ramifications. A select few vertebrate paleontologists, including Dale Russell and William Clemens, attended many of these conferences and contributed several papers to the conference publications, as well as publishing extinction-related papers in various scientific journals. I now provide a chronology of these conferences and publications, with particular emphasis on the work of Clemens, Russell, and other vertebrate paleontologists.

Clemens's first major published contribution to the impact debate was a 1981 article in the "Current Happenings" section of the journal *Paleobiology*, co-written with his former Ph.D. student, vertebrate paleontologist J. David Archibald of Yale University, and paleobotanist Leo J. Hickey of the Smithsonian Institution. In their article, entitled "Out with a whimper not a bang," Clemens, Archibald, and Hickey made several points about the impact/mass extinction hypothesis.[154] They argued that the asteroid hypothesis, and all other hypotheses of catastrophic extinction (the supernova hypothesis, the Arctic spillover hypothesis, etc.) share three basic assumptions: one, that the extinctions occurred globally, instantaneously, and synchronously; two, that the extinctions terminated otherwise prospering taxa; and three, that those species that became extinct

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[152] *Ibid.*, 240.
[153] *Ibid.*, 242; see also:
William Clemens, Archibald, and Hickey, "Out with a whimper not a bang," 295.

share some common factor or factors with which they can be categorized and their extinction understood. Their first priority was to separate the hypothesis of bolide impact, which was to be tested geologically and geochemically, from the hypothesis of mass extinction caused by bolide impact, which must be tested with reference to paleobiological data. Clemens et al also discussed the difficulties inherent in attempting to evaluate the synchroneity of extinction horizons in different rock facies. It cannot be assumed, for example, that the last appearance of Cretaceous foraminifera in a marine section is synchronous with the last appearance of Cretaceous dinosaurs in a terrestrial section; rather this is another hypothesis that must be tested. At the time of their writing, all that could be said with certainty about the synchroneity of extinctions at the K-T boundary was that all appeared to have occurred within the same interval of reversed polarity of the Earth's magnetic field (most likely chron 29R), which has a known duration of approximately 500,000 years.[155] Thus the greatest time resolution then possible was 500,000 years – an interval of time which could equally accommodate abrupt extinction by extraterrestrial means or gradual extinction through endogenous causes.

The same year, 1981, the first conference devoted exclusively to the Alvarez hypothesis and its ramifications was convened. It was the first of three Snowbird Conferences, so named because the first two were held in the ski resort town of Snowbird, Utah (the third 'Snowbird' Conference was actually held in Houston, Texas).

Snowbird I took place October 19 to 22, 1981. The title of the conference was "Large Body Impacts and Terrestrial Evolution: Geological, Climatological and Biological Implications." At Snowbird I, oceanic and atmospheric scientist O. Brian Toon of NASA presented a talk in which he demonstrated that a world-wide, impact-generated dust cloud would only block out sunlight for several months, not several years as the Alvarez team had originally proposed. As *Science* editorialist Richard A. Kerr reported on November 20, 1981, this news was greeted with some relief by paleontologists, who had argued all along that several years without sunlight would have

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[154] William Clemens, Archibald, and Hickey, "Out with a whimper not a bang," 293-298.
[155] *Ibid.*, 295.

caused an extinction much more severe than what the fossil record actually showed. Kerr wrote:

> ...a brief darkness appealed to paleontologists because it offered a means of decoupling the marine and terrestrial extinctions. With such a short-term darkness, the geochemists and planetary scientists could have their impact and paleontologists could have their gradual extinctions on land brought about by changing environmental conditions.[156]

While Kerr's decoupling of marine and terrestrial extinction sounded good in theory, in practice it just didn't work. The most diehard adherents of impact theory, most notably Luis Alvarez, still insisted that the impact hypothesis could account for *all* of the end-Cretaceous extinctions, particularly the extinction of the dinosaurs. In the face of their sweeping generalizations,[157] vertebrate paleontologists were goaded into defending the evidence of their discipline.

The volume of papers based on the conference, which was published in 1982 as a special paper of the Geological Society of America, was called *Geological Implications of Impacts of Large Asteroids and Comets on the Earth.*[158] Although some of the papers in the conference volume, particularly those written by biologists and paleontologists, were openly skeptical of the connection between the supposed impact and the K-T mass extinction, the majority did not question this link but enthusiastically set out to model the effects of a bolide impact on the Earth. For example, 28 of the 48 articles deal with the expected frequency of terrestrial impacts, evidence for terrestrial impacts, including cratering and geochemical markers, and the expected physical effects of impact. Among these papers is an article by the original Alvarez team summarizing the current evidence for impact, and revising their original estimate of a dust cloud obscuring sunlight for several years down to only several months (following Brian Toon's work).[159]

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[156] Richard A. Kerr, "Impact looks real, the catastrophe smaller," *Science* vol. 214, no. 4523 (November 20, 1981): 896.
[157] See for example:
Muller, *Nemesis, The Death Star*, 10.
Luis Alvarez, *Alvarez: Adventures of a Physicist*, 257.
[158] Leon T. Silver and Peter H. Schultz, eds. *Geological Implications of Impacts of Large Asteroids and Comets on the Earth: Geological Society of America Special Paper 190* (Boulder: The Geological Society of America, Inc., 1982).
[159] Walter Alvarez et al, "Current status of the impact theory," 305-315.

Fifteen of the 48 papers deal with the biological effects of impact and/or the biological record spanning the Cretaceous-Tertiary boundary. One of these papers is by Dale A. Russell. In an article entitled "A paleontological consensus on the extinction of the dinosaurs?"[160], Russell suggested that the current majority opinion among paleontologists that the end-Cretaceous extinction, particularly of dinosaurs, occurred gradually and as a result of solely terrestrial causes, is more a paleontological tradition than an established fact. Russell made several suggestions for further research into the exact nature of the K-T event, and pointed out that the record of latest Cretaceous dinosaur fossils is very poor and may not support a gradual interpretation.

Russell's article is immediately followed with a paper by William A. Clemens. In "Patterns of extinction and survival of the terrestrial biota during the Cretaceous/Tertiary transition,"[161] Clemens also addressed the inadequacy of the terrestrial fossil record, but argued that what little evidence there is supports a gradual, diachronous model of extinction, not an instantaneous, catastrophic one. His persistent use of the term 'K/T transition' rather than 'K-T boundary' or 'K-T extinction' underscores his reluctance to view the extinctions as occurring in one globally knife-sharp horizon, as the latter terms might be taken to imply. In this paper, Clemens argued first that a rigid definition of the terms 'catastrophic' and 'gradual' was required, to prevent (or at least reduce) potential confusion and overlap between the two extinction scenarios. Clemens suggested that a catastrophic extinction should be defined as one occurring within one lifetime of the longest-lived species to have become extinct during the time in question. Clemens estimated that the longest-lived dinosaur would probably have had a lifespan of approximately 100 years; he therefore defined a catastrophic extinction as one which took place in 100 years or less, and any extinction that lasted more than 100 years is thus gradual by definition. Clemens's definitions of catastrophic versus gradual seem unrealistically arbitrary, and not very useful besides; Clemens himself admitted that by this definition, even a mass extinction caused by bolide impact would be gradual, since

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[160] Dale A. Russell, "A paleontological consensus on the extinction of the dinosaurs?" in Silver and Schultz, eds. *Geological Implications of Impacts of Large Asteroids and Comets on the Earth,* 401-405.
[161] William A. Clemens, "Patterns of extinction and survival of the terrestrial biota during the Cretaceous/Tertiary transition," in Silver and Schultz, eds. *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, 407-413.

many of its effects would be secondary and would act over hundreds or thousands of years.[162]

Clemens broke down the Alvarez hypothesis even further in this paper. He now recognized three distinct hypotheses: one, that a bolide impact had taken place; two, that the bolide impact had caused the mass extinction of the marine biota; and three, that the bolide impact had caused the mass extinction of the terrestrial biota.[163] This separation of marine from terrestrial extinction does not seem logically necessary, as Clemens implies, but rather reflects a recognition of the very different types of fossil evidence and resolution available for the marine and terrestrial fossil records, as well as an acknowledgement of the difficulty inherent in comparing geographically and geologically distinct marine and terrestrial facies for chronological synchroneity.

Clemens then summarized the vertebrate fossil record of latest Cretaceous North America. Although Clemens admitted that the record of dinosaurs as currently understood is so poor that "we do not know whether the number of dinosaurian species in this area [Hell Creek Formation] increased, remained stable, decreased, or fluctuated with no *long-term* trend during this period," he noted that in those sections where dinosaur fossil-bearing rocks of Cretaceous age are overlain by rocks of Tertiary age, there is a gap of as much as three metres between the last dinosaur fossil and what is taken to be the K-T boundary.[164] Clemens noted that many small species of mammals, particularly marsupials, also became extinct at or by the end of the Cretaceous, and also that the extinctions of plants and animals in the Hell Creek area do not seem to have occurred at the same time. Clemens cited the lack of any "ecologically unifying criterion" as a point against the Alvarez impact hypothesis; the patterns of extinction and survival at the K-T are "too complex to attribute simply to an instantaneous causal factor, such as blocking the sun's light for a few months."[165]

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[162] *Ibid.*, 408.
[163] *Ibid.*, 408.
[164] *Ibid.*, 409, emphasis in original.
[165] *Ibid.*, 411.

The proceedings of Snowbird I contained two other papers, by vertebrate paleontologist Thomas J. M. Schopf[166] and geologist James E. Fassett,[167] that also rejected the hypothesis of dinosaur extinction by bolide impact. Schopf argued that the dinosaurs were in a gradual decline through the last few million years of the Cretaceous period, and most if not all of them went extinct somewhat below the boundary. Fassett, on the other hand, maintained that the bolide impact did not kill the dinosaurs because he found dinosaur bone above the impact horizon, indicating that at least some dinosaurs survived into the Tertiary. The conflicting theses of the latter two papers clearly illustrate the ambiguous nature of the end-Cretaceous dinosaur fossil record.

Clemens's next contribution to the issue of the K-T transition was an article in the journal *Acta Paleontologica Polonica*, published in 1983.[168] Here Clemens argued once again that the catastrophic impact hypothesis required global and instantaneous extinctions that followed from one primary or dominant cause, such as the blocking of sunlight for several months by an impact-generated dust cloud. Clemens seems to have recognized the logical fallacy of his other assertion, however, that catastrophic extinction hypotheses must cause the extinction of otherwise prospering lineages. While a gradual decline in a taxon prior to its sudden extinction must of necessity result from other, prior causes, finding evidence for such a decline does not rule out the possibility that a sudden catastrophe might have finished the taxon off.[169] Clemens analysed the fossil record of mammals in the latest Cretaceous Hell Creek Formation of Montana. He cautioned that the data are too coarse to interpret according to gradual or catastrophist theories of extinction, and noted also that the mammals of Hell Creek appeared to be diversifying or maintaining a static diversity, until some lineages appeared to go extinct abruptly, and at

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[166] Thomas J. M. Schopf, "Extinction of the dinosaurs: a 1982 understanding," in Silver and Schultz, eds. *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, 415-422.
[167] James E. Fassett, "Dinosaurs in the San Juan Basin, New Mexico, may have survived the event that resulted in creation of an iridium-enriched zone near the Cretaceous/Tertiary boundary," in Silver and Schultz, eds. *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, 435-447.
[168] William A. Clemens, "Mammalian evolution during the Cretaceous-Tertiary transition: evidence for gradual, non-catastrophic patterns of biotic change," *Acta Paleontologica Polonica* vol. 28, no. 1-2 (1983): 55-61.
[169] Geologist Ken Hsu expressed the same sentiment more succinctly: "A bomb on an old people's home is still a disaster." Kenneth J. Hsu, qtd. in Derek Ager, *The New Catastrophism: The Importance of the Rare Event in Geological History,* (Cambridge: Cambridge University Press, 1993), 186.

the same time as the dinosaurs.[170] Interestingly, however, Clemens did not interpret this sudden disappearance of hitherto-prospering mammals as evidence in favor of a catastrophic extinction. Instead, Clemens focused on the different types of mammals that became extinct – marsupials suffered much more than eutherians, and extinction patterns were different on floodplains versus river valleys.[171] The complexities of extinction and survival patterns suggested to Clemens that the K-T extinction, while geologically sudden, was too complex to attribute to a single causal factor like impact, and was instead the result of several interrelated terrestrial causes.[172]

It is interesting that Clemens referred in the body of the paper to a "geologically short… duration" for the K-T transition, yet in the title of the paper purported to discuss "gradual, non-catastrophic patterns of biotic change."[173] This apparent contradiction reflects the interplay between his earlier definition of catastrophic change as occurring over 100 years or less, and his tacit recognition that geologically sudden events may span several hundreds or thousands, if not tens of thousands, of years. Here we begin to see a curious aspect of Clemens's stance: he insisted that the asteroid hypothesis, if correct, must restrict its effects to a period of 100 years or less, and then argued for the incorrectness of the impact hypothesis by documenting fossil changes that appear to have taken place over thousands of years. However, Clemens had elsewhere acknowledged that secondary effects of a bolide impact might well take more than 100 years to be felt, that changes which take place over thousands of years are geologically (if not biologically) sudden, and that in any case, the current understanding of the fossil record did not permit a chronological understanding anywhere near fine enough to discriminate on scales of hundreds or even thousands of years.[174]

In his next article, co-authored with his former student J. David Archibald, Clemens once again reiterated his cautions about the incompleteness of the terrestrial vertebrate fossil record, but (again) expressed his belief that the evidence was more supportive of gradual than catastrophic causal factors. Archibald and Clemens wrote in

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[170] William Clemens, "Mammalian evolution during the Cretaceous-Tertiary transition," 59
[171] *Ibid.*, 59.
[172] *Ibid.*, 60.
[173] *Ibid.*, 60.

their contribution to W. A. Berggren and John A. Van Couvering's 1984 book *Catastrophes and Earth History: The New Uniformitarianism,* that "Clearly what has been discovered in eastern Montana does not support hypotheses invoking a sudden, cataclysmic event as the causal factor."[175]

Another conference on the mass extinction question was held in 1983. From August 10 to 12, a symposium on "Dynamics of Extinction" was held at the Northern Arizona University, in Flagstaff, Arizona. An eponymous volume of papers based on the proceedings was published in 1986 and edited by geologist David K. Elliott.[176] *Science* published an editorial on the conference, written by Roger Lewin, on September 2, 1983. Lewin noted that "the meeting was biased in favor of those who lean toward earthbound, as against extraterrestrial, agents as a cause of, specifically, the late Cretaceous extinction." [177] He also discussed the sparseness of the terrestrial/vertebrate fossil record:

> Do the fauna disappear rapidly at the boundary or diminish slowly towards it, the paleontologists wish to know. In trying to answer this question it has become painfully clear that apart from the marine microfossil record the available data are just too ambiguous to provide immediate solution.[178]

Elliott's book based on the conference proceedings included a chapter by paleontologist Digby J. McLaren on "Abrupt extinctions." McLaren pointed out that historically, gradualism was incorporated as a theoretical presupposition into both stratigraphy and evolution, and it is only recently, with the advent of the Alvarez impact hypothesis and Eldredge and Gould's concept of punctuated equilibrium, that this paradigm of gradualism has been seriously questioned.[179] The concepts of gradual, uniformitarian change in evolutionary biology and geology were of particular importance to vertebrate paleontologists, as discussed in Chapter 1.

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[174] Clemens, "Patterns of extinction and survival of the terrestrial biota during the Cretaceous/Tertiary transition," 408.
[175] J. David Archibald and William A. Clemens, "Mammal evolution near the Cretaceous-Tertiary boundary," 339-371, in Berggren and Van Couvering, eds., *Catastrophes and Earth History: The New Uniformitarianism*, 366.
[176] David K Elliott, ed., *Dynamics of Extinction* (New York: John Wiley & Sons, Inc., 1986.)
[177] Lewin, "Extinctions and the history of life," 935.
[178] *Ibid.*, 936.
[179] Digby J. McLaren, "Abrupt extinctions," in *Dynamics of Extinction*, David K. Elliott, ed., 37-46 (New York: John Wiley & Sons, Inc., 1986), 37-38.

In a chapter entitled "Mesozoic tetrapod extinctions: a review," dinosaur paleontologist Edwin H. Colbert presented a somewhat hazy picture of dinosaur extinction, in which some species appear to decline before the K-T boundary, while many others disappear suddenly at the boundary. In this paper, as in his writings elsewhere, Colbert did not come down firmly on the side of gradualism or on that of catastrophism.[180]

Next is William A. Clemens's chapter on "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition."[181] Clemens once again analysed the vertebrate fossil record of the Hell Creek Formation in Montana. Clemens lamented the fact that too many authors simply assume that the extinction of dinosaurs was both abrupt and synchronous with the marine mass extinction, when in fact this is a hypothesis that should be tested by actually examining the vertebrate fossil record. Clemens then proceeded to do exactly that, listing the terrestrial and freshwater vertebrate survivors and victims of the K-T extinction, down to the genus level. According to Clemens's data, the highest extinctions of terrestrial vertebrates occurred among non-avian dinosaurs (100% generic extinction), pterosaurs (100% generic extinction), and eolacertilian lizards (represented by one genus, which went extinct). High rates of extinction were also seen in marsupial mammals (75% generic extinction) and chondrichthyan fishes (60% generic extinction). By contrast, most other small reptiles and mammals had high survival rates, with the result that only 57% of terrestrial vertebrate genera in total went extinct, at the Hell Creek location. Clemens also suggested that ornithischian dinosaurs suffered a reduction in generic diversity prior to their extinction, although he admitted that "Total saurischian and ornithischian diversity in the Western Interior study area, assessed by comparison of the numbers of families recorded from the Judithian and the Lancian [stages], was effectively stable."[182]

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[180] Edwin H. Colbert, "Mesozoic tetrapods: a review," in *Dynamics of Extinction*, David K. Elliott, ed., (New York: John Wiley & Sons, Inc., 1986), 49-62.
See also: Edwin H. Colbert, *Dinosaurs: An Illustrated History* (Maplewood: Hammond Incorporated, 1983), 199-207.
[181] William A. Clemens, "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," in David K. Elliott, ed., *Dynamics of Extinction*, (New York: John Wiley & Sons, Inc., 1986), 63-85.
[182] *Ibid.*, 75.

In this paper, as in previous papers, Clemens once again acknowledged the inadequacy of the vertebrate fossil record in allowing scientists to discriminate between catastrophic and gradual extinction. He referred to the currently available terrestrial fossil record as "geographically limited and temporally coarse."[183] Clemens also wrote "it is clear that a temporal lag existed between extinctions of Cretaceous lineages and appearances of new groups of mammals"[184], which would rule out any theories of extinction by competition with mammals and would tend to support a catastrophic model of extinction.[185] Nevertheless, once again Clemens favored a gradual over a catastrophic explanation. He pointed out that there is strong evidence for both marine regression and climatic cooling at the end of the Cretaceous, and suggested that the observed extinction and survival rates are more compatible with such gradual climatic changes than with an abrupt catastrophe such as a bolide impact. Clemens concluded with a pointed reminder that the extinction question can only be solved by actually examining "the probable causes of extinction of individual lineages, not from the imposition of a hypothesis that dictates the cause of their extinction."[186] This quotation highlights the incommensurability of the approaches of vertebrate paleontologists versus impact supporters: Clemens (and other paleontologists) wished to use the fossil record as the starting point for inquiry into the mass extinction question, whereas the Alvarez team (and many other impact supporters) sought evidence for impact, on the assumption that if impact was proved, then its causal link to the mass extinction was also proved.

Somewhat different was the second Snowbird Conference, held October 20 to 23, 1988, proceedings of which were published in 1990. The conference and the subsequent volume were both called *Global Catastrophes in Earth History: an Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality.*[187] It can be seen from this more conservative title that the seven years between Snowbird I and Snowbird II saw a

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[183] William Clemens, "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," 72.
[184] But see Sloan et al, "Gradual dinosaur extinction," 629-633.
[185] *Ibid.*, 74.
[186] William Clemens, "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," 78.
[187] Virgil L. Sharpton and Peter D. Ward, eds. *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality* Geological Society of America Special Paper 247. (Boulder: The Geological Society of America, Inc., 1990).

theoretical separation of the impact hypothesis from the impact-as-extinction-cause hypothesis; a recognition of the difficulty in defining a mass extinction (hence the more neutral reference to 'mass mortality'); and an acknowledgment that other factors, such as volcanism, might have caused or contributed to the extinction.

The conference volume included 58 articles. Of these 58, 25 dealt with the evidence for and/or modeling of bolide impacts; eight dealt with massive volcanism; four addressed the periodic impact and/or periodic extinction hypothesis; eight examined the invertebrate fossil extinction record; three examined the extinction record among terrestrial plants; and only two dealt with the vertebrate fossil record. The remaining four articles explored theoretical and/or social aspects of the impact debate.

The first of the two papers on the vertebrate fossil record was "Rocks, resolution, and the record; a review of depositional constraints on fossil vertebrate assemblages at the terrestrial Cretaceous/Paleogene boundary, eastern Montana and western North Dakota," by vertebrate paleontologist and geologist David E. Fastovsky.[188] In this paper, Fastovsky presented his interpretation of the Hell Creek Formation in Montana and North Dakota. Unfortunately, the Hell Creek Formation was deposited by a meandering stream system, which constantly cut new channels through older sediments, confusing the age distribution of the sedimentary layers and reworking fossil deposits. Fastovsky cautioned that fluvial systems like Hell Creek are dominated by sedimentary, not biological, processes, and that any attempted estimation of species diversity must take geological as well as biological factors into account.

The second paper discussing the vertebrate fossil record was "Differential Cretaceous/Tertiary extinctions of nonmarine vertebrates; evidence from northeastern Montana," by vertebrate paleontologists J. David Archibald and Laurie J. Bryant, who both completed their Ph.D. studies at Clemens's institute, the University of California at Berkeley.[189] Archibald and Bryant documented the extinction and survival rates among vertebrate species and families across the K-T boundary at Hell Creek. After correcting

[188] David E. Fastovsky, "Rocks, resolution, and the record; a review of depositional constraints on fossil vertebrate assemblages at the terrestrial Cretaceous/Paleogene boundary, eastern Montana and western North Dakota," in Virgil L. Sharpton and Peter D. Ward, eds. *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality* Geological Society of America Special Paper 247. (Boulder: The Geological Society of America, Inc., 1990), 541-548.

for reworking into younger channels (which would artificially increase survival rates) and rarity effects (which would artificially decrease survival rates) Archibald and Bryant concluded that the overall survivorship level of vertebrate species across the K-T was approximately 53%. Archibald and Bryant argued that such high survival rates showed that the catastrophic kill mechanisms proposed by impact proponents were too severe.[190]

Although the title and contents of the Snowbird II conference proceedings indicated that some headway had been made in decoupling the hypotheses of bolide impact and impact-as-extinction-cause, as well as allowing the volcanist proponents to be heard, the majority of contributions to this volume (as discussed above) still concentrated only on amassing proof of impact itself.

In response to Archibald and Bryant's Snowbird II paper, invertebrate paleontologist Peter M. Sheehan and geologist/biologist David E. Fastovsky conducted their own survey of vertebrate survival across the K-T boundary in eastern Montana.[191] Sheehan and Fastovsky eliminated Archibald and Bryant's correcting factor for rare species, and found that while 90% of freshwater vertebrate species survived, only 12% of land-dwelling vertebrates survived. Sheehan and Fastovsky argued that this "pattern of extinction and survival is compatible with the hypothesis of an asteroid impact after which there was a temporary cessation of primary, photosynthetic productivity."[192] The authors concluded that an asteroid impact would have devastated marine and terrestrial food chains but increased the amount of organic detritus carried out to sea in river systems, and because most freshwater organisms feed on such detritus, their higher survival rates are compatible with the impact extinction model.[193] Sheehan and Fastovsky do not discuss why these freshwater organisms were not killed by the intense acid rain which would have been another consequence of a bolide impact.

The third Snowbird Conference, entitled "New Developments Regarding the K-T Event and Other Catastrophes in Earth History", was held in Houston, Texas, on February 9 to 12, 1994. The subsequent volume was published in 1996 under the title

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[189] Archibald and Bryant, "Differential Cretaceous/Tertiary extinctions," 549-562.
[190] *Ibid.*, 561.
[191] Peter M. Sheehan and David E. Fastovsky, "Major extinctions of land-dwelling vertebrates at the Cretaceous-Tertiary boundary, eastern Montana," *Geology* vol. 20 (June 1992): 556-560.
[192] *Ibid.*, 556.

The Cretaceous-Tertiary Event and Other Catastrophes in Earth History,[194] and exhibited much the same distribution of subject material as the proceedings of Snowbird II. This volume included 39 papers. Twenty-three of the 39 articles dealt with evidence for and/or modeling of bolide impacts; two compared the relative effects of impact and massive volcanism; three dealt with events at other extinction horizons besides the K-T; and seven discussed the K-T mass extinction with reference to specific fossil evidence. Of these seven paleontological papers, five discussed the invertebrate/marine fossil record, and only two examined the vertebrate/terrestrial record. The first of these two papers was "Models of vertebrate mass mortality events at the K/T boundary", by Alan H. Cutler and Anna K. Behrensmeyer.[195] Cutler and Behrensmeyer responded to other scientists who had suggested that if a bolide impact did cause a sudden mass extinction at the end of the Cretaceous period, evidence of mass dying, including charred dinosaur bone beds, should have been found. Cutler and Behrensmeyer argued that the population density of dinosaurs and the nature of the fossil record are such that large bone beds should not be expected even if all dinosaurs were killed instantly by bolide impact.

The second paper was "The significance of the extinction of the dinosaurs" by Dale A. Russell. Russell compared the relative fitness of Paleozoic, Mesozoic, and Cenozoic faunas by analyzing their respective biodiversity, encephalization ratios, and metabolic rates. Russell found that the latest Cretaceous dinosaurs were rapidly becoming more 'fit', and that they more closely resembled their Cenozoic replacements that their Paleozoic ancestors. After the extinction of the dinosaurs, the mammals and birds that replaced them quickly attained and then surpassed the dinosaurs' level of fitness. Russell concluded therefore that the K-T mass extinction was not a significant

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[193] *Ibid.*, 558-559.

[194] Graham Ryder, David Fastovsky, and Stefan Gartner, eds. *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History: Geological Society of America Special Paper 307* (Boulder: The Geological Society of America, Inc., 1996).

[195] Alan H. Cutler and Anna K. Behrensmeyer, "Models of vertebrate mass mortality events at the K/T boundary," in Graham Ryder, David Fastovsky, and Stefan Gartner, eds., *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History*. Geological Society of America Special Paper 307 (Boulder: The Geological Society of America, Inc., 1996), 375-379.

setback in evolutionary terms.[196] Russell also clearly indicated his support of the impact/extinction hypothesis:

> It should be apparent that their [the dinosaurs'] record is too incomplete to resolve time scales comparable to those of a bolide impact. However, that a bolide impact was the cause of their extinction is abundantly implied by trace element, isotopic, mineralogic, and microfossil evidence.[197]

By making this statement, Russell echoed other vertebrate paleontologists in saying that the dinosaur fossil record itself does not show proof of extinction-by-impact, but also echoed other impact supporters in attributing the dinosaur extinction to the bolide impact through admittedly abundant, but still circumstantial, evidence.

In 1996, Norman MacLeod and Gerta Keller, two of the minority of invertebrate paleontologists who did not support the impact hypothesis, published a volume entitled *Cretaceous-Tertiary Mass Extinctions: Biotic and Environmental Changes*. This volume was based on a session by the same name at the Annual Meeting of the Geological Society of America, in 1993. In their introduction, editors MacLeod and Keller explained the necessity for their book:

> At this time the most neglected aspects of the impact/extinction controversy are the lack of sufficiently detailed predictions that identify the types of organisms most at risk by the various proposed killing mechanisms, and our almost complete ignorance of the K-T transition for many benthic marine invertebrate and terrestrial (vertebrate and invertebrate) groups.[198]

The volume comprised 19 articles, including three that discussed some aspect of vertebrate paleontology. Only one article (which discussed the extinctions of a particular group of microscopic marine organisms) attributed the K-T mass extinction to impact. Eight articles invoked only endogenous extinction mechanisms, and 6 articles suggested that both gradual terrestrial processes and impact had contributed to the extinction.[199]

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[196] This statement appears to contradict other statements Russell has made; for instance, astrophysicist Richard Muller wrote in 1988: "Dale [Russell] once told me that he felt the evolution of intelligence may have been set back millions of years when the dinosaurs were destroyed." (Muller, *Nemesis, The Death Star*, 77.)

[197] Dale A. Russell, "Significance of the extinction of the dinosaurs," in Ryder, Fastovsky, and Gartner, eds. *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History*, 386.

[198] MacLeod and Keller, "Introduction," 5.

[199] The remaining four articles either omitted discussion of extinction mechanisms, or discussed groups which did not become extinct at the K-T.

The level of support for the impact hypothesis is much lower in this volume than in the proceedings of the pro-impact conferences, which suggests that a significant number of paleontologists were opposed to the impact hypothesis, but were not being heard at other venues.

The debate has also been examined, if only fleetingly, as a case study in the history, philosophy, and sociology of science. On July 12, 1991, at the Biannual Meeting of the International Society for the History, Philosophy, and Social Studies of Biology, at Northwestern University, the impact/mass extinction debate was discussed by the scientific players themselves and by historians, philosophers, and sociologists of science. The outcome of this discussion was a collection of essays and interviews entitled *The Mass-Extinction Debates: How Science Works in a Crisis*, edited by William Glen and published in 1994.[200] With the exception of an article written by sociologist Elisabeth S. Clemens, which is not relevant to the present discussion,[201] Glen's book is the only historical/sociological account of the impact/mass extinction debates published thus far.[202] In the first two chapters, Glen provided a detailed chronology of the impact debate and a breathless analysis of social factors operating within the debate, including the role of disciplinary magisters and the use of mathematical and physical models by scientists of varying disciplines.[203] Glen stated that a scientist's discipline or sub-discipline played an important role in determining his or her choice of extinction hypotheses, and noted that of all scientists, vertebrate paleontologists as a group were least likely to ascribe to the impact hypothesis. However, except for noting that the vertebrate fossil record is sparser than and qualitatively different from the invertebrate fossil record, Glen offered no explanation for this observation.[204]

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[200] William Glen, ed., *The Mass-Extinction Debates: How Science Works in a Crisis* (Stanford: Stanford University Press, 1994).
[201] Elisabeth Clemens, "Of asteroids and dinosaurs," 421-456.
[202] Several scientist participants have written articles and/or books in which they express their opinions on various social, political, and theoretical aspects of the debate, but these comments are not grounded in current historiographical or sociological theory, and neither are these authors trained in history or sociology of science.
[203] William Glen, "What the impact/volcanism/mass-extinction debates are about," in Glen, ed., *The Mass-Extinction Debates*, 7-38.
William Glen, "How science works in the mass-extinction debates," in Glen, ed., *The Mass-Extinction Debates*, 39-91.
[204] Glen, "How science works in the mass-extinction debates," 52.

Sociologist of science Elisabeth S. Clemens contributed a chapter on "The impact hypothesis and popular science: conditions and consequences of interdisciplinary debate."[205] Clemens argued that the debate began with, and is therefore grounded in, the popular question "What suddenly killed the dinosaurs?" Clemens stated that impact supporters have resisted paleontologists' attempts to reframe this question, since such a change would detract from the debate's popular appeal. For paleontologists, Clemens wrote, "the verdict appears to be both Scottish and Victorian: not proven, but nice people don't speak about such things."[206] Clemens noted that paleontologists have long viewed the extinction of the dinosaurs as a gradual event[207], and pointed out that the paleontologists' desire to treat the extinction as a complex event has not appealed to impact supporters or the scientific or popular press,[208] but does not offer any explanation (beyond their prior adherence to gradualism) for why paleontologists have remained primarily silent on the impact/mass extinction issue.

Glen's book also includes a transcription of an interview with William Clemens.[209] In this interview, Clemens reiterated his support for a gradual, endogenous extinction model, emphasized that the Alvarez theory really comprised two hypotheses (impact and impact-caused-extinction), and rejected Glen's suggestion that adherence to uniformitarianism had been a major barrier to the acceptance of the impact hypothesis among Earth scientists.[210] Glen's attempt to write a book encompassing the entirety of the impact debate, with discussions of the contributions made by all relevant disciplines, did not allow room for much detailed analysis to be focused on any one of these disciplines. In consequence, there is little else in the book of relevance to the present discussion.

Finally, a very small number of vertebrate paleontologists have published books on the subject of the impact/mass extinction debate. In 1996, J. David Archibald published a book entitled *Dinosaur Extinction and the End of an Era: What the Fossils*

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[205] Elisabeth Clemens, "The impact hypothesis and popular science," 92-120.
[206] *Ibid.*, 109.
[207] *Ibid.*, 93.
[208] *Ibid.*, 109-110.
[209] William Clemens, "On the mass-extinction debates: an interview with William A. Clemens, conducted and compiled by William Glen," 237-252.
[210] Ibid., 239.

Say.[211] Archibald's book is primarily an amplification of his and Bryant's 1990 examination of the survival and extinction rates among end-Cretaceous terrestrial vertebrates, combined with an expansion of their regression and habitat fragmentation theory into a sophisticated and well-reasoned model of terrestrial extinctions. Archibald argued that since most known dinosaurs are from coastal areas, it is possible that they preferred to live in coastal environments, and the massive reduction in coastal area at the end of the Cretaceous might have contributed to dinosaur extinction. Terrestrial habitats would also have been fragmented and extended at the same time, as regression re-established land bridges and connections, but as lengthening stream systems fragmented land areas. Habitat fragmentation would again be hardest on large terrestrial vertebrates like dinosaurs, which needed larger areas than smaller vertebrates to live and feed in, while new land connections would allow for the immigration of competitors from different areas and the influx of new diseases, potentially detrimental to all terrestrial organisms. Archibald also claimed that his regression model best explained the selective extinction of sharks and other brackish-water dwellers, while freshwater organisms escaped virtually unscathed: lengthening river systems would increase living area for purely freshwater organisms, but would be stressful for organisms which need to access salt water part or most of the time.[212]

Archibald compared the actual extinction and survival rates among the various groups of organisms with those predicted by the impact hypothesis, the volcanist hypothesis, and his own regression/habitat fragmentation model, and concluded that the regression model accounted for the observed extinction pattern in 11 out of 12 terrestrial vertebrate groups, while impact and volcanism together were only compatible with the observed extinctions in 5 of the 12 vertebrate groups.

Archibald's book was an example of the direction in which vertebrate paleontologists wanted the impact debate to go: away from the assumption that if there was a bolide impact, it must have caused the K-T extinction, and therefore the specific effects of impact could be assumed to be sufficient to account for the observed extinctions; and towards an actual examination of the evidence of the fossil record. That

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211 Archibald, *Dinosaur Extinction and the End of an Era.*
212 *Ibid.*

most vertebrate paleontologists accepted the fact of bolide impact, but were not content to assume a connection between the impact and the mass extinction, was documented in several surveys, which I will now discuss.

Over the past twenty years, several authors have conducted surveys of various scientific communities to determine the level of support given by scientists of those communities to the Alvarez impact hypothesis, and other hypotheses of mass extinction. The first and best known of these polls was done by Antoni Hoffman and Matthew H. Nitecki in 1984, and reported in the periodical *Geology* in 1985.[213] Hoffman and Nitecki questioned 172 *Paleobiology* subscribers, 82 American geophysicists, 118 British paleontologists, 113 German paleontologists, 122 Polish geoscientists, and 20 Soviet geoscientists on their level of interest in and self-assessed expertise on the Alvarez impact hypothesis, and also determined where the respondents first encountered the Alvarez hypothesis.[214] They also asked which of four possible extinction scenarios most closely matched the respondents' opinions regarding the cause of the K-T extinction (Figure 3). Hoffman and Nitecki only provided these data according to the above national and subscriptive categories, but it is possible to work backwards from the percentages provided in their Table 2 to obtain the number of people in each category who selected each of the four causal options.[215] By then adding across categories, I determined that in total, 16.4% of respondents felt that there was an impact at the K-T boundary and that it caused the mass extinction; 31.1% believed there was an impact but that other factors caused the mass extinction; 20.7% did not believe there was an impact at the K-T boundary; and 10.0% did not believe there was a mass extinction at the K-T boundary.[216] If one eliminates the geoscientists and considers only the paleontologists

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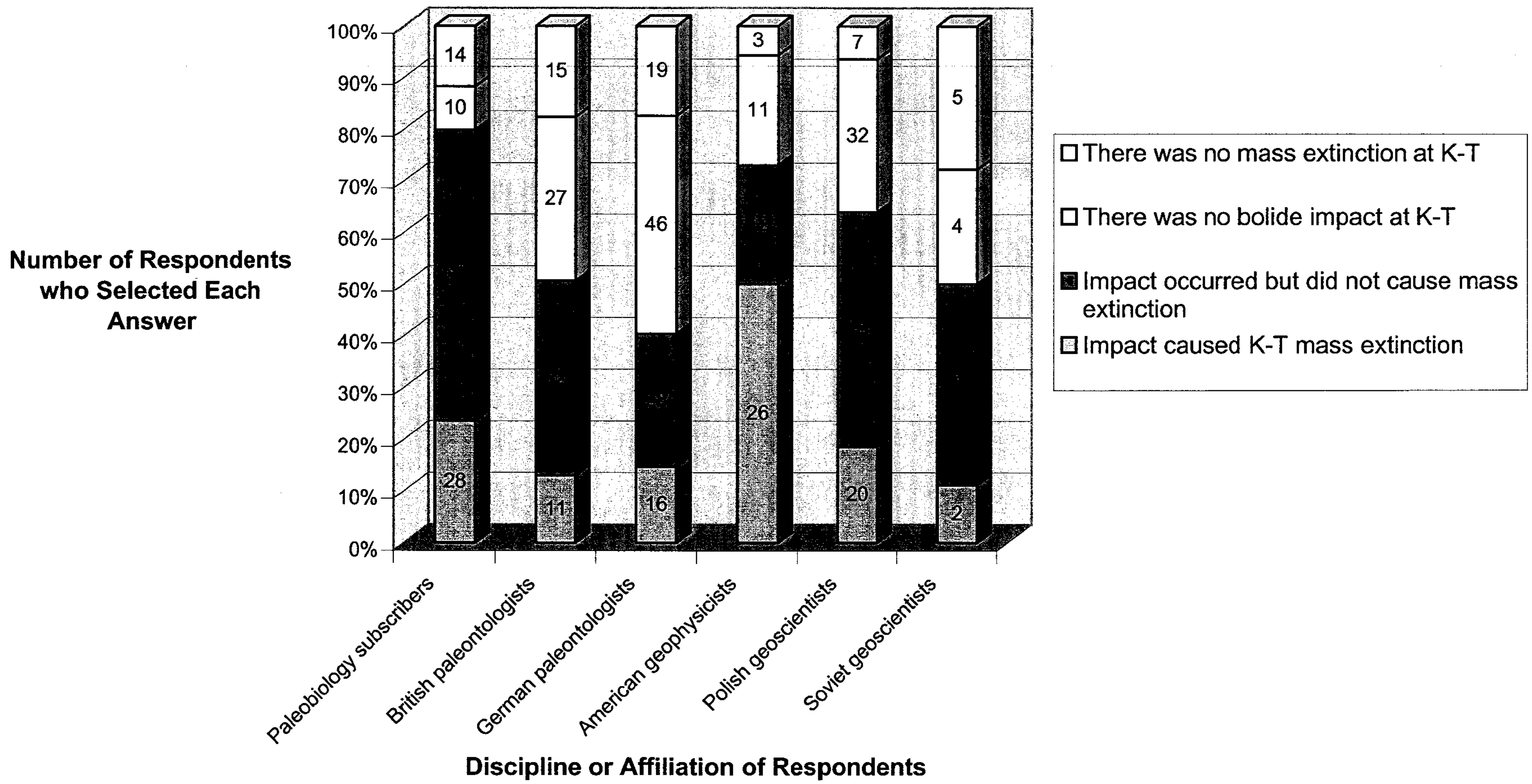
213 Antoni Hoffman and Matthew H. Nitecki, "Reception of the asteroid hypothesis of terminal Cretaceous extinctions," *Geology* vol. 13 (December 1985): 884-887.
214 *Ibid.*, 885.
215 *Ibid.*, 886.
216 Powell, *Night Comes to the Cretaceous*, 162-163. Powell discussed the Hoffman and Nitecki poll and also provided a blanket percentage of adherents to each of the four proposed extinction scenarios. However, Powell's percentages differ slightly from mine: he wrote that 24% believed the impact caused the extinction, 38% believed there was an impact but it did not cause the mass extinction, 26% did not believe there was an impact, and 12% did not believe there was a mass extinction. It is not possible to arrive at Powell's figures using any information in the Hoffman and Nitecki paper as published; perhaps Powell had access to Hoffman and Nitecki's raw data. Hoffman and Nitecki did state in their paper that the percentages provided did not add up to 100% because some respondents did not select any one of the four

Figure 3. Responses to Survey by Hoffman and Nitecki, 1984 (n=627)



and subscribers to *Paleobiology* (two thirds of whom, according to Hoffman and Nitecki, are also paleontologists)[217], the figures show that 13.6% believed the impact caused the extinctions; 31.5% believed there was an impact but other factors caused the extinctions; 20.1% believed there was no impact; and 11.9% believed there was no mass extinction. These percentages add up to a total of 77.1%, indicating that fully 22.9% of paleontologists who completed the survey did not choose any one of the four categories.

Journalist Malcolm W. Browne of the *New York Times* conducted a poll on the dinosaur extinction question at the annual meeting of the Society for Vertebrate Paleontology (SVP) held in October 1985 in Rapid City, South Dakota.[218] In a subsequent editorial, Browne stated that 118 of 300 attendees participated in this poll – which means that 182 attendees, fully 61%, did not participate. Of the 118 participants, 5 (4%) attributed the dinosaurs' extinction to a bolide impact; 51 (43%) believed there was an impact but it did not cause the mass extinction; 12 (10%) did not believe there was an impact; and 32 (27%) believed there was no mass extinction of vertebrates at the K-T boundary.[219] These numbers add up to 100, which suggests that among the 118 or 39% of attendees who chose to take part in the poll, a further 18 chose not to respond to that particular question (Figure 4).

In a 1987 article in *Paleobiology*, dinosaur paleontologist Peter Dodson reported on a Dinosaur Systematics Symposium held at the Royal Tyrrell Museum of Palaeontology in Drumheller, Alberta, June 2 to 5, 1986.[220] The symposium included a poll on the "tempo of dinosaur extinction."[221] Dodson stated that 38 of the 50 attendees (76%) voted for gradual dinosaur extinction, 4 (8%) voted for catastrophic extinction, and one (2%) was undecided. Dodson did not indicate if the remaining 7 attendees abstained from the vote or were absent at the time the poll was taken.

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proposed extinction scenarios; if Powell was able to make his calculations using respondent totals which eliminated these abstainers, this might explain why his calculations differ slightly from mine.

[217] Hoffman and Nitecki, "Reception of the asteroid hypothesis," 884.

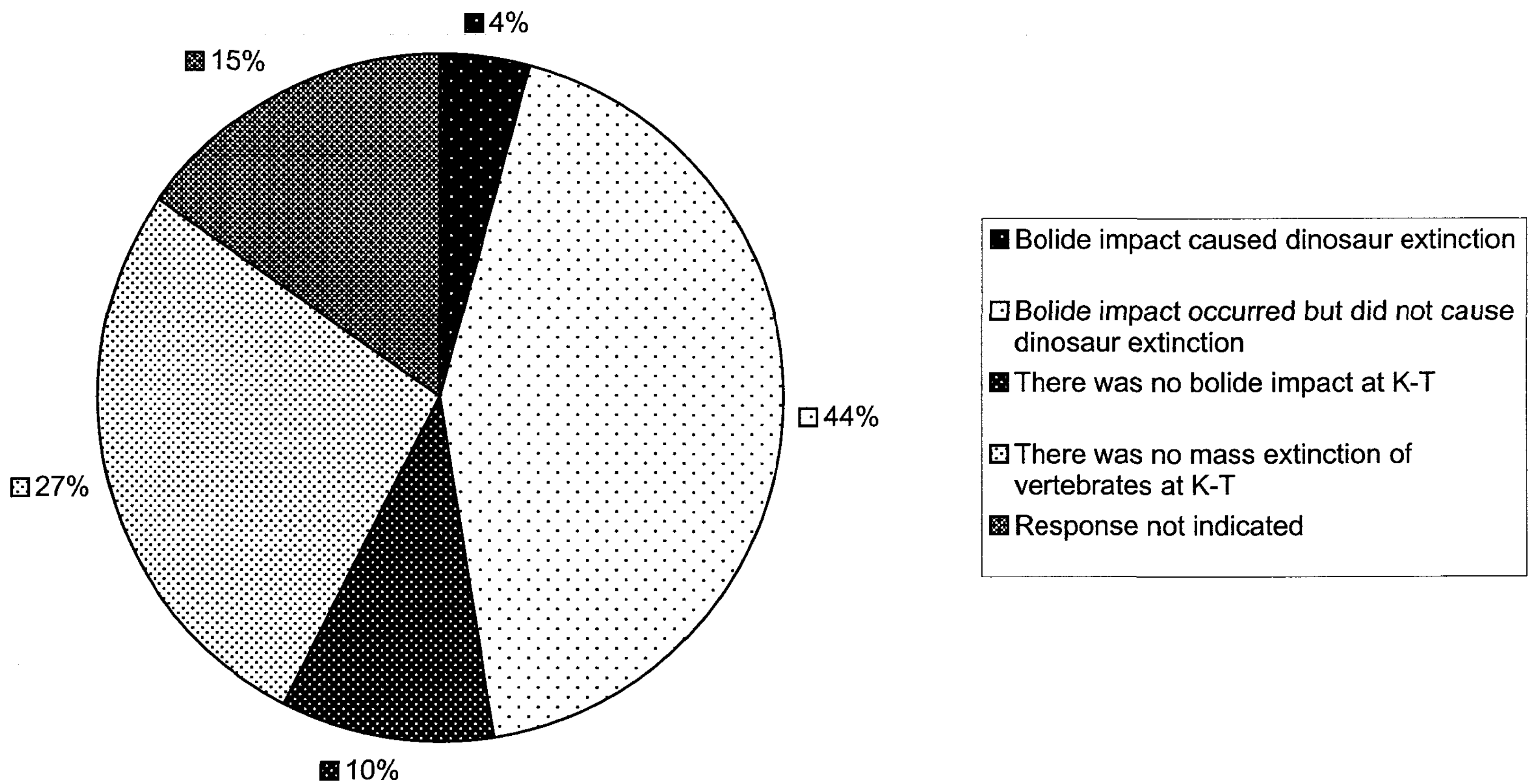
[218] Malcolm W. Browne, "Dinosaur experts resist meteor extinction idea," *New York Times* (October 29, 1985), C3.

[219] *Ibid.*, C3.

[220] Peter Dodson, "Review: Dinosaur Systematics Symposium, Tyrrell Museum of Palaeontology, Drumheller, Alberta, June 2-5, 1986," *Paleobiology* vol. 7, no. 1 (March 1987): 106-108.

[221] *Ibid.*, 108.

Figure 4. Responses to Survey by Browne, October 1985 (n=118)



Finally, in late 1996, engineer Cyril Galvin distributed a questionnaire to attendees at meetings of the Geological Society of Washington, the Geophysical Laboratory of the Carnegie Institute of Washington, the Paleontological Society of Washington, and the Potomac Geophysical Society. Of 159 attendees in total, 72 responded to Galvin's survey. Among these 72 respondents, Galvin identified 12 paleontologists (although he does not specify how many are vertebrate versus invertebrate paleontologists). Galvin's first question asked if respondents believed there had been "a geologically significant impact, or series of impacts... on the earth's surface at the end of Cretaceous time."[222] All twelve paleontologists answered yes.

Galvin also posed two questions inquiring as to the cause of the dinosaurs' extinction. The first of these questions (question four, in Galvin's numbering) had the following phrasing: "Did the impact(s) cause the extinction of dinosaurs?" Four of the twelve paleontologists answered no, and six answered yes. Galvin stated that two other paleontologists chose two of the three possible answers (yes, no, no opinion). He does not say which two answers were chosen, but logic suggests that they were 'yes' and 'no', indicating that those two paleontologists believed that impact(s) had contributed to the dinosaurs' extinction but other causes had contributed as well.[223] The second question (Galvin's question six) regarding dinosaur extinction asked respondents to make the following choice of extinction causes: "Dinosaurs went extinct because of Impact(s), Vulcanism [sic], or Other_______________."[224] To this question, three paleontologists answered 'impact(s)', and seven paleontologists did not give an answer. Galvin did not indicate which choice(s) the remaining two paleontologists picked. Neither question allowed respondents to clearly indicate a belief that two or more causes were jointly responsible for the dinosaurs' extinction. The conflicting results for these questions probably reflect the different meanings inherent in their phrasing: the first question asks if impact caused the extinction, but without explicitly ruling out the potential influence of

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[222] Cyril Galvin, "Essay review: *The Great Dinosaur Extinction Controversy* and the K-T research program in the late 20th century," *Earth Sciences History* vol. 17, no. 1 (1998): 45.

[223] It would be illogical for respondents to answer both 'no opinion' and either 'yes' or 'no', for if they truly had no opinion they would probably not also express an assenting or dissenting opinion, as a 'yes' or 'no' choice would indicate. It is more logical to suppose that the two respondents who gave more than one answer selected 'yes' and 'no'. This choice might indicate that the respondents agreed that impact was one cause of the dinosaurs' extinction, but that other cause(s) were also in operation.

other causes, while the second question seems to imply that whatever answer respondents picked would state *the* cause (singular) of the extinction.

Galvin's results indicate that paleontologists accepted that there was an impact at the end of the Cretaceous period but that many of them did not believe the impact was the (sole) cause of the K-T mass extinction. Galvin suggested several reasons for the paleontologists' stance, including territorialism, the difficulty of establishing synchroneity using the geological and fossil record, and the modest level of current understanding of the dinosaur fossil record near the K-T boundary.[225]

Taken together, the results of these various polls indicate that most paleontologists believe that there was a bolide impact at the end of the Cretaceous period, but that many paleontologists do not believe that it was the (sole) cause of the mass extinction. The lowest support for impact as extinction cause was obtained at the Dinosaur Systematics Symposium reported on by Dodson. This was a meeting of vertebrate paleontologists who specialize in dinosaur studies. The impact hypothesis also received only minor support at the SVP meeting reported on by Malcolm Browne. The Society for Vertebrate Paleontology includes scientists who study all vertebrate groups, not just dinosaurs. The similarity of results between these two polls indicates that the impact/mass extinction hypothesis was rejected by the majority of the vertebrate paleontology community.

In contrast, Galvin and Hoffman and Nitecki found that geoscientists were much more supportive of the Alvarez theory. In response to Galvin's question six, half of the non-paleontologists who gave a single answer attributed the dinosaurs' extinction to impact. Hoffman and Nitecki found that the majority of American geoscientists believed that the bolide impact caused the K-T mass extinction, while the majority of British paleontologists and *Paleobiology* subscribers agreed there was an impact but believed the mass extinction was caused by other factors. These data confirm that the majority of vertebrate paleontologists rejected impact as the cause of the mass extinction.

It is also interesting to note the large numbers of paleontologists who chose not to participate in the various polls, or who chose not to answer some questions if they did

[224] Galvin, "Essay review," 46.
[225] Galvin, "Essay review," 47-48.

participate.[226] Hoffman and Nitecki found that 22.9% of responding paleontologists did not answer their question on the cause of the K-T mass extinction. Of the twelve paleontologists who filled out Galvin's questionnaire, seven (58.3%) did not answer question six (although all twelve answered the arguably more open-ended question four, and none of the twelve chose 'no opinion' as his or her response). When journalist Malcolm Browne conducted his poll at the SVP meeting, 118 attendees (61%) did not participate. These figures suggest that a large number of vertebrate paleontologists did not want to publicly express their opinions on the cause of the Cretaceous-Tertiary mass extinction, particularly not to members of the press, like Malcolm Browne. Or, perhaps, one might conclude that vertebrate paleontologists did not want to display publicly their *lack* of support for the Alvarez hypothesis.[227]

The most recent of the above polls was conducted seven years ago, in 1996. I conducted my own survey in late 2002 to early 2003 to determine the present status of the impact hypothesis among vertebrate paleontologists.[228] I surveyed twenty-five members of the VRTPALEO Listserver, an online email community associated with (but administered independently from) the Society for Vertebrate Paleontology.[229] I posted an email to the VRTPALEO community inviting interested members to fill out a six-question survey, and sent the survey to anyone who responded to this email. There were twenty-five members who completed and returned the survey, comprising sixteen Ph.D.s, five Ph.D. candidates, two M.Sc.s, one M.Sc. candidate, and one paleontologist with other qualifications[230] (Figure 5). Sixteen of the respondents currently reside in the

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[226] As mentioned above, seven attendees (14%) of the Dinosaur Systematics Symposium did not participate in the poll which was held there, but as Dodson does not indicate whether these seven people were present but abstained from participating, or were simply absent, I cannot draw any conclusions about their willingness or reluctance to express their opinions on the extinction issue.

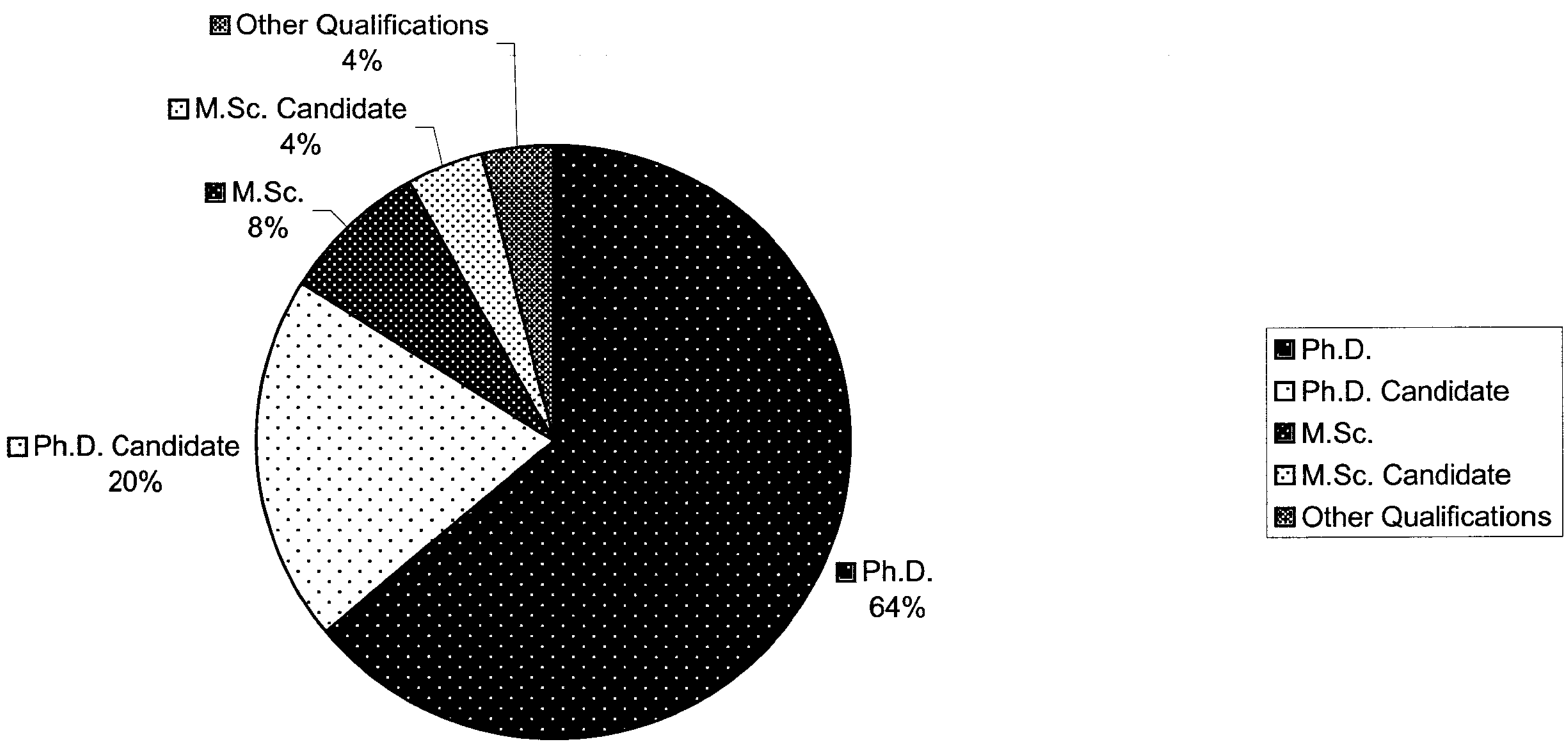
[227] Several authors have reported that scientists publishing or publicly expressing anti-impact opinions were prejudiced against in such matters as acceptance of papers for publication, the awarding of research grants, and even consideration for employment. See for example Browne, "Dinosaur experts resist meteor extinction idea," C3, and Officer and Page, *The Great Dinosaur Extinction Controversy*, 79-89.

[228] Keynyn Longman, "K-T impact debate survey," *Survey of subscribers to VRTPALEO Listserver, owned by Sam McLeod* (November 2002-February 2003). See Appendix C for a copy of the email and survey posted to the VRTPALEO Listserver, and Appendix D for raw data and tables. I conducted the survey under my married name, which was Longman, but I have since reverted to my maiden name (Brysse), under which this thesis is authored.

[229] The VRTPALEO Listserver is owned by Dr. Sam McLeod of the University of Southern California.

[230] This respondent works as a museum curator and studies non-mammalian vertebrates, but does not possess a formal degree in paleontology, as far as I was able to ascertain.

Figure 5. Level of Education of VRTPALEO Listserve Survey Participants (n=25)



United States, three reside in Canada, three are in the United Kingdom, and three are in other European countries (one each in France, Germany, and Sweden) (Figure 6). The majority of respondents (18 people or 72%) expressed a belief that the K-T mass extinction resulted from a combination of gradual terrestrial processes followed by a bolide impact. Five respondents (20%) identified a bolide impact as the sole cause of the mass extinction. One respondent (4%) professed uncertainty over the cause of the mass extinction, and one respondent (4%) questioned the reality of the mass extinction itself (Figure 7). In response to a question regarding the duration of the K-T extinction, the majority of respondents gave answers compatible with gradual, not catastrophic, extinction mechanisms (Figure 8).

I was somewhat surprised that 20% of my respondents believed the impact was the sole cause of the extinction, and I attempted to plot the respondents' preferred extinction theory against their respective levels of education (Figure 9). Although the sample size in this survey is too small to permit any firm conclusions to be drawn, I note that the impact hypothesis received more support among vertebrate paleontologists still in training than among those who have already received their doctorates. These data suggest that a Kuhnian paradigm shift may be occurring, in which a younger generation of paleontologists, who, having grown up with the impact theory, are more open to it, is replacing the older generation of paleontologists for whom the impact theory represented such an alien point of view.[231]

In this chapter, we have seen that while vertebrate paleontologists came to accept that a bolide impact had occurred, most (with the exception of Dale Russell) did not believe that the impact caused the K-T mass extinction. We have also surveyed the limited number of contributions made by vertebrate paleontologists to the debate. We are left with the following questions: why did so few vertebrate paleontologists participate in the impact/mass extinction debate, and on what specific grounds did vertebrate paleontologists reject the impact hypothesis? These questions are the focus of Chapter 4.

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[231] Thomas S.Kuhn, *The Structure of Scientific Revolutions*, 3rd ed. (Chicago and London: The University of Chicago Press, 1996), 151-159.

Figure 6. Current Country of VRTPALEO Listserve Survey Participants (n=25)

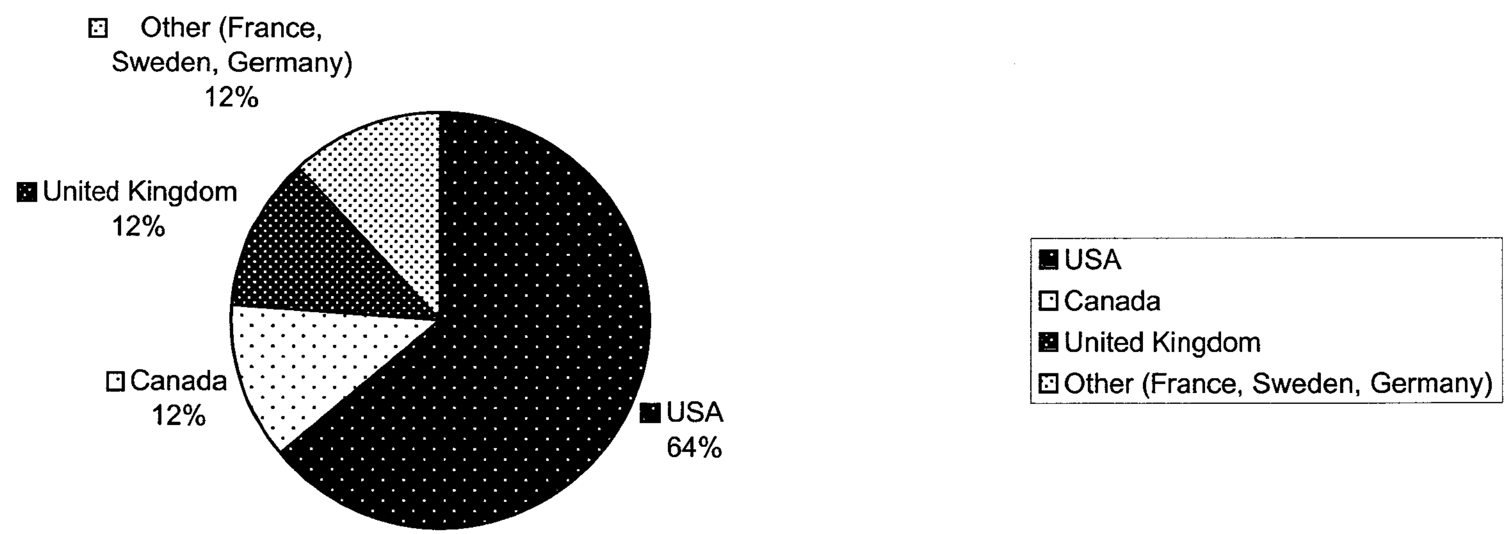


Figure 7. Cause of K-T Mass Extinction As Stated by VRTPALEO Listserve Survey Participants (n=25)

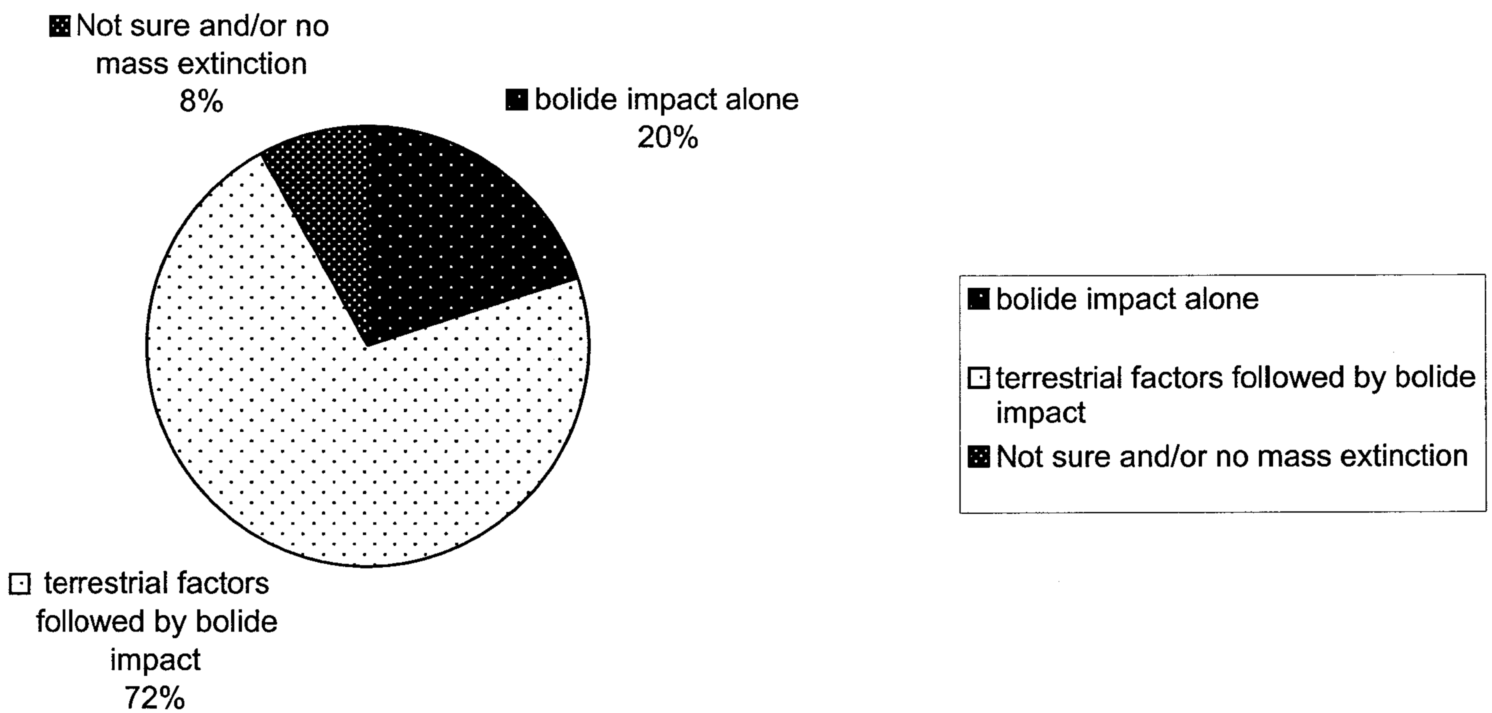


Figure 8. Duration of K-T Mass Extinction As Stated by VRTPALEO Listserve Survey Participants (n=25)

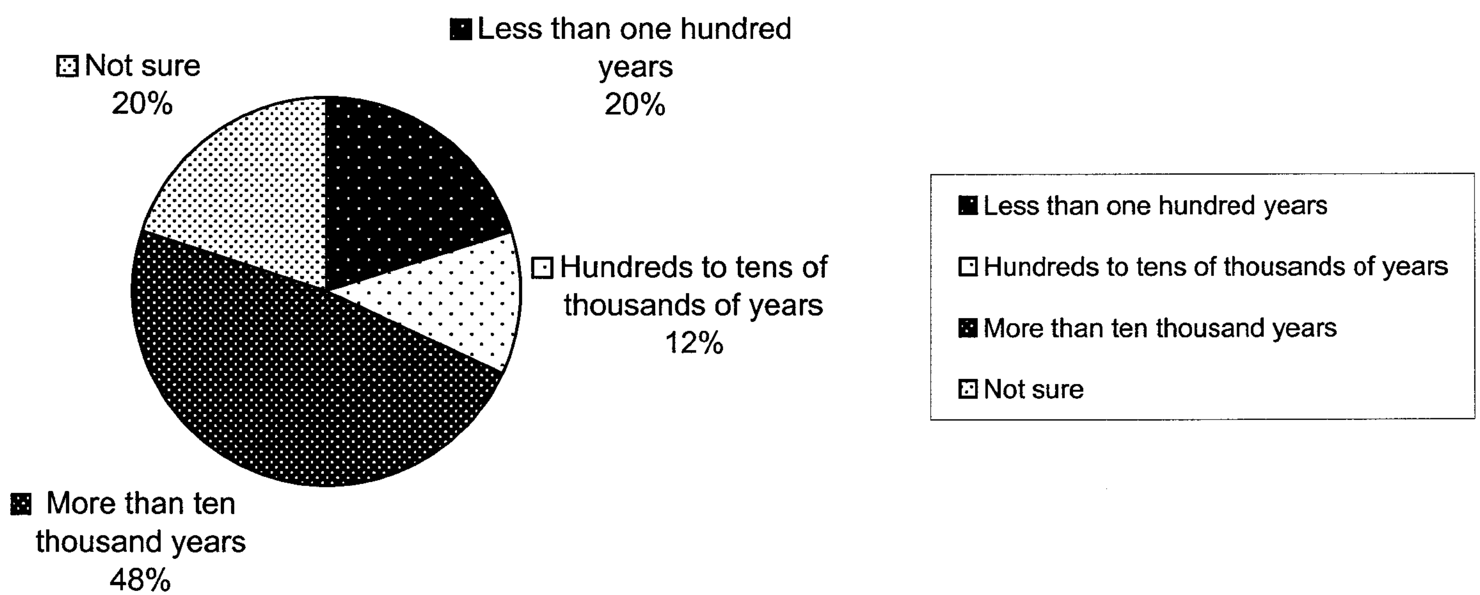
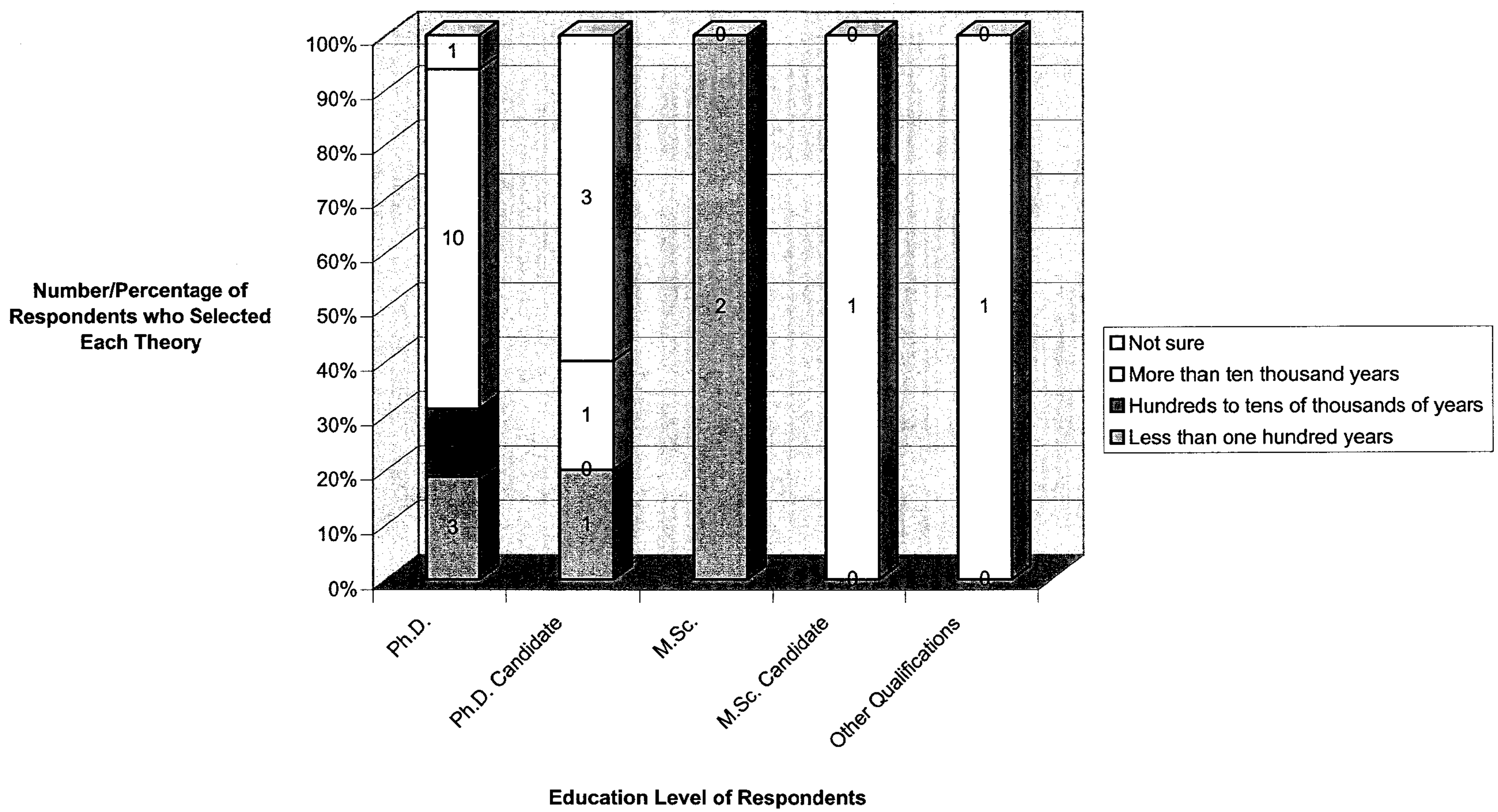


Figure 9. Extinction Theories Supported by VRTPALEO Listserve Survey Respondents, According to Participants' Level of Education (n=25)



Chapter 4: The Rejection of the Impact Hypothesis

As we have seen in the previous chapter, vertebrate paleontologists challenged the Alvarez impact hypothesis on several points. As mentioned earlier, a few other participants in/commentators on the debate have briefly discussed the vertebrate paleontologists' reluctance to embrace the impact theory. For example, in his book *The Nemesis Affair: A Story of the Death of Dinosaurs and the Ways of Science*, invertebrate paleontologist David M. Raup presented a list of eleven arguments condensed from the early reactions of scientists, particularly paleontologists, to the Alvarez hypothesis.[232] Raup's list could be categorized as seven scientific, two theoretical, and two social arguments (by my definition). Sociologist Elisabeth Clemens also briefly discussed the rejection of the impact theory by vertebrate paleontologists; she emphasized the role of the perceived hierarchy of sciences and the conflict between what she called 'the tension between biological complexity/geological imprecision and astrophysical simplicity'.[233]

Whereas previous authors have documented (but not explained) vertebrate paleontologists' rejection of the Alvarez hypothesis, or have chosen to focus only on what they believed was the main reason behind this rejection, in this chapter I will discuss all of the objections I have encountered in the arguments presented by vertebrate paleontologists against the impact hypothesis, or in defense of alternative extinction theories. In most cases the paleontologists themselves have not sorted their objections into particular categories, and a few objections appear implicitly rather than explicitly in the sources I have examined. I have separated these objections, stated and implied, into theoretical, social, and scientific grounds. What I call theoretical grounds are objections not to the scientific evidence itself, but to the theories or assumptions which underlie the evidence. The adherence to ideals of uniformitarianism and gradualism identified by so many authors as a key factor in this debate is an example of an objection on theoretical grounds – although I believe the impact hypothesis has clashed with other theoretical presuppositions than the uniformitarian ideal. Social grounds include reactions to the perceived hierarchy of sciences and the attitudes of various players in the debate; in other

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[232] Raup, *The Nemesis Affair*, 70-71.
[233] Elisabeth Clemens, "Of asteroids and dinosaurs," 431-432.

words, these were objections to the players themselves and the way they presented their arguments, not the arguments themselves. Finally, the category of scientific grounds describes the objections vertebrate paleontologists raised based on the scientific evidence of their own discipline.

These categories are and must be somewhat arbitrary; nevertheless I feel they will be valuable tools in the present analysis. My objective in employing these categories is twofold: first, this identification of different types of objections allows me to separate the theoretical and social grounds – which often were not stated explicitly – from the scientific grounds behind which they were hidden. These implicit objections can be brought to light only if they are drawn out from the shadow of the scientific grounds within which they were frequently embedded. Second, in discussing the vertebrate paleontologists' scientific objections, I demonstrate that while vertebrate paleontologists did have strong evidentiary reasons for doubting the validity of the impact hypothesis, these scientific objections in many cases served as disguises, vehicles, or justifications for the theoretical and social grounds which formed the primary basis on which vertebrate paleontologists rejected the Alvarez hypothesis. On the basis of this argument, I present the theoretical and social grounds first and the scientific grounds last, because I believe that these more social objections affected the ways in which vertebrate paleontologists perceived the scientific evidence, thus colouring the scientific grounds on which they challenged the impact hypothesis.

Theoretical Grounds For Rejecting the Alvarez Hypothesis

As we have seen, modern paleontology rested on the assumptions of uniform geological processes and gradual evolutionary change.[234] A belief that significant bolide impacts had occurred only in the period of early bombardment of the solar system further cemented the conviction that catastrophic events had no place in the scientific analysis of the history of life on Earth. Several authors have attributed the initial skepticism of earth scientists towards the Alvarez hypothesis to a theoretical commitment to these three tenets of paleontology and geology, particularly to the concept of uniformitarianism.

[234] See Chapter 1.

Marvin, for example, stated that adherence to the doctrine of uniformitarianism has been the single largest barrier to the acceptance of the Alvarez impact hypothesis.[235] Glen, in his 1994 book on *The Mass-Extinction Debates*, attributed the poor reception of impact hypotheses before Alvarez to "untestability, a strong anti-catastrophic community gestalt, and a general lack of familiarity with bolide impacts".[236] In his book *T. rex and the Crater of Doom*, Walter Alvarez wrote that gradualism was "dogma" in geology and paleontology, and noted that catastrophic hypotheses of extinction "contradict[ed] all the training and experience of geologists and paleontologists."[237] Dinosaur paleontologist Dale A. Russell agreed, writing in 1982 that:

> [Under Lyell's influence] catastrophism fell from favor, to be replaced by the doctrine of gradualism. For more than a century now paleontologists have generally agreed that whatever may have caused the disappearances at the end of the Mesozoic era, it could not have been a worldwide catastrophe.[238]

While gradualism, unfamiliarity with recent impacts, and particularly uniformitarianism did play some role in the reluctance of vertebrate paleontologists to embrace the Alvarez impact hypothesis, this thesis as it stands is too simplistic. It states that uniformitarianism and gradualism constituted a paradigm in paleontology and implies that paleontologists could not or would not look beyond this paradigm. One major reason to suspect that adherence to the uniformitarian dogma was not as solid a wall as it seemed is the eagerness of so many authors, inside and outside the paleontological and geological communities, to name it as the villain, and the fact that they have done so from the beginning of the impact debate. If uniformitarianism were so firmly entrenched in the earth sciences, would its practitioners have so easily been able to step outside its influence and comment on its workings? Further thought suggests that these commitments may have had less influence than is popularly assumed, while other, more subtle theoretical influences were also at play.

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[235] Marvin, "Impact and its revolutionary implications for geology," 147-154.

[236] Glen, "How science works in the mass-extinction debates," 39. From the context, Glen appeared to be referring to the reception of impact hypotheses among geologists and paleontologists.

[237] Walter Alvarez, *T. rex and the Crater of Doom*, 58-59.

[238] Russell, "The mass extinctions of the late Mesozoic," 58.

In his book *The Nemesis Affair*, Raup discussed several pre-Alvarez impact hypotheses, which were all ignored by contemporaneous scientists. Raup suggested that such theories, when they were proposed, were "too far out to be heard against the backdrop of the Lyellian paradigm – that is, too incredible even to register, much less argue about."[239] The Alvarez hypothesis, by contrast, not only 'registered' but captured the attention of scientists of all disciplines, and spawned a host of articles, conferences, and book publications. The differing receptions of Alvarez versus previous impact hypotheses indicates that some change had taken place in the intervening time that made the Alvarez theory appear less 'incredible' when it was proposed.

As we saw in Chapter 1, several changes did indeed take place through the 1960s and 1970s. The burgeoning space program and a re-examination of terrestrial craters forced a realization that bolide impacts occurred more frequently and more recently than previously supposed. This proof of occasional catastrophic impacts, combined with Stephen Jay Gould's doubts about the validity of substantive uniformitarianism and his work with Niles Eldredge on punctuated equilibrium, served to weaken the influence of uniformitarianism on geology and vertebrate paleontology before 1980, with the result that when the Alvarez team proposed their impact hypothesis, the idea was no longer "unthinkable"[240] or "beyond the pale."[241]

This analysis is supported by the players themselves. For example, vertebrate paleontologist J. David Archibald wrote, in his 1996 book *Dinosaur Extinction and the End of an Era*:

> Scientists (I among them) who are unwilling to jump on the impact bandwagon because we take our scientific skepticism seriously are sometimes unfairly portrayed as geological Neanderthals. Peter Ward... and Stephen Jay Gould [two invertebrate paleontologists who have ascribed impact theory's negative reception to a misplaced insistence on uniformitarianism]... maintain that impacting has not been regarded as a potentially important Earth process, including mass extinction [sic], because establishment geologists have viewed it as somehow violating an important concept in geology known as uniformitarianism. Such an

[239] Raup, *The Nemesis Affair*, 42.
[240] Ibid., 40. The impact hypothesis was "unthinkable" when McLaren proposed it in 1970, to explain the Frasnian-Fammenian extinction.
[241] Glen, "How science works in the mass-extinction debates," 42. Glen is also referring to the reaction to McLaren's impact/extinction idea; at that time, the idea of impact-driven extinction was "beyond the pale".

> assessment creates the proverbial straw man. Ward and Gould are just suggesting that most earth scientists retain a nineteenth century view of uniformitarianism, and thus they cannot accept extraterrestrial impacts as the major cause of the mass extinction – whatever the evidence. These authors conveniently fail to note that the concept of uniformitarianism has changed since its inception some two hundred years ago.[242]

William Clemens, in a 1994 interview with William Glen, stated: "I would take issue with the view that vertebrate paleontologists or other scientists routinely reject any hypothesis that invokes catastrophic events of kinds that have not been experienced during historic times."[243]

In other words, uniformitarianism was on the wane before the Alvarez team presented their impact hypothesis.[244] I propose that adherence to the doctrine of uniformitarianism was presented by so many authors as the main reason why paleontologists rejected the impact hypothesis precisely *because* at that moment geologists and paleontologists were *emerging* from the influence of uniformitarianism. To earth scientists in general, and impact supporters among them in particular, its incompatibility with impact theory was one more proof of the limitations of the uniformitarian paradigm. The majority of vertebrate paleontologists, on the other hand, since they did not support the impact hypothesis, laboured under the dual burdens of the accusation of fanatical adherence to uniformitarianism, and the necessity to articulate and prove their 'real' objections to Alvarez theory.

While uniformitarianism and gradualism did not constitute such major theoretical objections as some authors have suggested, vertebrate paleontologists did have other theoretical objections that negatively predisposed them to the Alvarez theory. These theoretical objections stemmed not from arguments over particular scientific facts and their possible interpretation, but rather from a deeper commitment to theoretical ideals in paleontology, and to deeply rooted convictions about the proper way to do science. The latter convictions are shared to some extent by all scientists, but manifest themselves uniquely in a paleontological context, as we shall see.

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242 Archibald, *Dinosaur Extinction and the End of an Era*, 202.
243 William Clemens, "On the mass-extinction debates: an interview with William A. Clemens, conducted and compiled by William Glen," 239.
244 See Chapter 1.

1) Impact Theory Operated Outside Of Natural Selection

The first of these theoretical objections involves the traditional paleontological view of evolution. Darwin established, and modern biologists and paleontologists agree, that evolution is not teleological: it does not progress towards some predetermined goal. As organisms evolve they do not become better or higher in any absolute sense, but only become better adapted to the particular environmental conditions that surround them. Nevertheless, before the advent of the impact hypothesis, evolution was seen as a developmental and constructive process. An analogy, as suggested by Peter J. Bowler in his book *Evolution: The History of an Idea*, is the big bang theory in cosmology.[245] The big bang theory presents a developmental model of the universe, in that it began in one particular state and developed into a different state. The crucial difference between such a developmental model and its alternative, a steady-state model, is that the former "involves a *direction* of change from a beginning to a quite different end point", while the latter shows "mere fluctuations about a mean."[246] Although the big bang does not imply a teleological imperative in the universe's creation and subsequent evolution, it does involve directional development. In the same way, paleontologists and biologists have viewed the evolution of life on Earth as a developmental process.

Even while rejecting the idea of teleology, it has proved difficult for biologists and paleontologists to resist ascribing to some form of biological directionalism. As paleontologists have long been aware, life has developed from unicellular to multicellular forms; from marine to terrestrial environments; from invertebrate to vertebrate animals – in short, the evolution of life has led not only towards more complex forms, but also better adapted and more competitive forms. Bowler wrote in 1989 that "most people still imagine that evolution is an essentially progressive process", and noted that Darwin himself "could not escape the common feeling that in some ways modern forms of life are more advanced than their earliest ancestors."[247] This directional development implies progress in the sense of directional change, even though it does not entail progress in the sense of developing toward a goal.

[245] Bowler, *Evolution: The History of an Idea*, 10.
[246] *Ibid.*, 10, emphasis in original.
[247] *Ibid.*, 9-11.

The concept of intra- and inter-specific competition provides a mechanism for such directional biological change: if organisms and species are in constant competition with each other such that only the fittest survive to reproduce, the overall fitness of organisms and species must be increasing in some absolute sense. Before the impact theory, extinction was thought of as the mechanism by which the less fit species were eliminated. As invertebrate paleontologist David M. Raup noted, extinction itself was therefore a constructive process, whereby "less well-adapted organisms are eliminated, leading to improvement in the mean adaptive level of the total biota."[248]

But the impact theory forced a reassessment of the concepts of natural selection and constructive evolution. The impact of a 10-kilometre asteroid or comet was not an event that any species could have become adapted to survive; the survivors of such an impact could not therefore be considered more fit than the victims – only luckier. As Raup wrote:

> … It may be that extinction, although selective, is not constructive. If mass extinctions are the result of environmental stresses so rare as to be beyond the 'experience' of the organisms, extinction may be just a matter of the chance susceptibility of the organisms to these rare stresses. … The result would be a highly selective extinction, but one having no constructive effect in terms of the general success of organisms in normal times. … [T]he effects are not constructive in the usual Darwinian sense.[249]

The implications of this idea of impact as a non-constructive force in evolution are far-reaching. Paleontologists were forced to reconsider not only that dinosaurs may have been less unfit than previously supposed, but also that the rise of the mammals might have resulted not from their evolutionary superiority but only an accidental opportunity. Geologist Karl Flessa and geologist/biologist David Jablonski asked, in a 1983 article in *Paleobiology*: "Is the world's biota a carefully weeded and ever-improving garden, or is it just an assortment of whatever species happen to have survived

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[248] David M. Raup, "Biological extinction in Earth history," 1532.
[249] *Ibid.*, 1532.

the last extinction?"[250] Their slightly incredulous tone captured the puzzled attitude of paleontologists in the wake of the impact hypothesis.

Invertebrate paleontologist Peter M. Sheehan and vertebrate paleontologist Dale Russell, in their contribution to the 1994 conference volume *Hazards Due to Comets and Asteroids*, wrote:

> This resistance [by paleontologists towards the impact theory] may be in part because a new paradigm would be required to explain the evolutionary history of life on Earth. Paleontologists have operated under a long-accepted paradigm of gradual evolutionary change dominated by competition between organisms. ... If the impact rather than competition from mammals caused the extinction of the dinosaurs, the organisms may have been passive as a driving force in large-scale ecosystem change other than during adaptive radiations. The paradigm of evolutionary replacement needs to be revised.[251]

If a bolide impact caused the end-Cretaceous mass extinction, its victims could not have died because they were unfit in terms of normal selective pressures, nor could its survivors have lived because they were somehow more fit in times of normal selection. The impact of an asteroid or comet is an event outside of normal evolution, and as such did not fit into existing paleontological theory when it was proposed. As the evidence above suggests, the challenge it presented to then-accepted ideas about evolution as a constructive force was one factor in making the impact theory difficult for vertebrate paleontologists to credit.

Dale Russell was perhaps the only vertebrate paleontologist in a position to understand or appreciate this revolutionary new concept when it first arose, because of his work on dinosaur intelligence and dinosaur extinction. As discussed in Chapter 3, Russell's evaluation of *Troodon* as a creature with the potential to develop a high level of intelligence led him to believe that dinosaurs were very successful in evolutionary terms, and might have evolved into the niche we humans now possess if they had not gone extinct. Because of his beliefs regarding dinosaur intelligence, Russell could not view the extinction of the dinosaurs as the removal of an unfit group of species. His diversity

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[250] Karl Flessa and David Jablonski, "Extinction is here to stay", *Paleobiology* vol. 9, no. 4 (Fall 1983), 320.

analysis also convinced him that the dinosaurs had disappeared in an abrupt catastrophe, which further disposed him to attribute their extinction to some random, unlucky event. Because of its compatibility with his own research and beliefs, Russell immediately understood and supported the Alvarez impact hypothesis. Other vertebrate paleontologists, who had not had prior reasons to question their beliefs about the constructive nature of the extinction process, resisted the new idea.

2) Impact Theory Contravened Principle of Parsimony

> Articles by volcanists and paleontologists have sometimes closed with the telling sentiment that they find satisfaction in seeking an earthly cause [for the K-T mass extinction] before turning to the sky.[252]

The principle of parsimony, also known as Occam's Razor, is an important principle in paleontology, as in other sciences. This principle tells us that, all else being equal, the simplest hypothesis tends to be the correct one. Parsimony has proven of particular importance in paleontology and evolutionary biology over the last forty years, since the introduction of cladistics. Cladistics is a particular type of phylogenetics, or in other words, a specific method for attempting to determine the ancestral relationships or a family tree of a group of organisms. Cladistics was first proposed by the German biologist W. Hennig in the 1950s, although his ideas were not widely read until the mid-1960s. Cladistics differs from other types of phylogenetic reconstruction in that it is based only on the possession of shared derived characters, and it only permits holophyletic groups: groups containing the ancestor and all of its descendants.[253] In constructing a cladogram, or family tree based on cladistics, the principle of parsimony is employed to determine which of several possible trees is likely to be the correct one, or the one that most closely approximates the true evolutionary relationships of the

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[251] Peter M.Sheehan and Dale A. Russell, "Faunal change following the Cretaceous-Tertiary impact: using paleontological data to assess the hazards of impacts," in Tom Gehrels, ed., *Hazards Due to Comets and Asteroids* (Tucson and London: The University of Arizona Press, 1994), 881.

[252] Glen, "What the impact/volcanism/mass-extinction debates are about," 9.

[253] Ernst Mayr and Peter D. Ashlock, *Principles of Systematic Zoology*, 2nd ed. (New York: McGraw-Hill, Inc., 1991), 274-275. It is cladistics, by the way, that tells us birds are dinosaurs: since birds evolved from dinosaurs, 'Dinosauria' is not a legitimate (=holophyletic) group unless this name identifies the creatures commonly called dinosaurs *and* all of their descendants, including birds.

organisms in question. It is assumed that episodes of convergent evolution, where the same trait arises independently in two unrelated or distantly related groups, are rare, and therefore, species or clades which share a large number of traits are probably closely related. The best tree is thus assumed to be the shortest one; the one that branches from the ancestral species to the descendant species using the smallest number of evolutionary steps, and includes the smallest number of episodes of convergent evolution. In this way, the principle of parsimony – used in constructing the shortest tree – is used as a fundamental principle in the reconstruction of evolutionary relationships between organisms.

Paleontologists have employed the principle of parsimony to create cladograms reconstructing the relationships of extinct species, just as biologists use it to examine the relationships of living species, and parsimony is therefore an important general principle among paleontologists as well as biologists. Paleontologists became familiar with parsimony specifically in its application to cladistics, but also more broadly in its context as a principle of science in general.

Some paleontologists have applied the principle of parsimony to argue against the Alvarez impact hypothesis. For example, vertebrate paleontologist Thomas J. M. Schopf wrote: "As far as is currently known, it does not seem *necessary* to invoke an unusual event to account for the demise of the dinosaurs."[254] Likewise, mammal paleontologist William A. Clemens also expressed his belief that terrestrial explanations are to be considered before extraterrestrial ones:

> Paleobiological data cannot rule out the possibility of the occurrence of supernovae, asteroid impacts, or other extraordinary events. ... However, analyses of the paleobiological data suggest such an event is *not required* to explain the biotic changes during the Cretaceous-Tertiary transition.[255]

Invertebrate paleontologist David M. Raup also listed the principle of parsimony in his summary of arguments advanced by paleontologists against the Alvarez hypothesis: "There is no need or justification to invoke extraterrestrial forces to solve earthly problems. The *deus ex machina* was discarded years ago."[256] That this

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[254] Schopf, "Extinction of the dinosaurs: a 1982 understanding", 421 (emphasis added).
[255] William Clemens, Archibald, and Hickey, "Out with a whimper not a bang," 297 (emphasis added).
[256] Raup, *The Nemesis Affair*, 71.

application of the principle of parsimony in rejecting the Alvarez hypothesis is common among paleontologists is evident from the following *National Geographic* article:

> [M]any scientists refuse to accept that such catastrophes [impact leading to forest fires, devastating winds, lightning, etc.] have caused the great dyings. 'We don't need an impact,' I have heard over and over from paleontologists. 'We can explain mass extinctions with earthly causes.'[257]

Dale Russell also noted these objections made by his fellow vertebrate paleontologists, but attributed them to a slightly different motive than a desire to employ the principle of parsimony. Russell suggested that in the case of causal mechanisms for mass extinction, what most of his colleagues identify as the 'simplest' explanation is the one which conforms best to preexisting theory (i.e. gradualism) and provides the smallest shock to the current belief system:

> [W]hen a paleontologist is approached with a catastrophic solution to a biostratigraphic problem, he [sic] is more apt to react with polite reserve than with enthusiasm. He would probably recommend that his friend formulate a series of working hypotheses and select, as the most favored, one that is both congruent with existing data and satisfies the principle of minimum astonishment.[258]

In the view of many vertebrate paleontologists, then, it appears that the simplest explanation for the K-T mass extinction was one that invoked only known, terrestrial causes, whereas the invocation of unfamiliar, extraterrestrial causes should be seen as a more complicated, and therefore less likely, explanation.

Surprisingly, Walter Alvarez agreed with this assessment, as he wrote in a 1986 *Eos* article: "[I]f a set of geological data can be explained by common, gradual, well-known processes, that should be the explanation of choice."[259] However, Alvarez went on to say: "[B]ut... when the evidence strongly supports a more sudden, violent event, we will go where the evidence leads us."[260] Alvarez clearly believed that the evidence in this case pointed to a sudden, violent extinction event.

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[257] R. Gore, "Extinctions: what caused the earth's great dyings?" *National Geographic* (June 1989), 673.
[258] Russell, "A paleontological consensus on the extinction of the dinosaurs?" 402.
[259] Walter Alvarez, "Toward a theory of impact crises," 654.
[260] *Ibid.*, 654.

This issue of adherence to the principle of parsimony has therefore exposed several different layers of conflict. All of the players appeared to agree that Occam's razor should only be used to choose between equally likely alternatives; in other words, parsimony does not supersede what the actual evidence indicates. Many vertebrate paleontologists argued that the invocation of terrestrial mechanisms was more parsimonious than the invocation of extraterrestrial mechanisms. Some paleontologists (as we will see in the section on scientific objections) believed the evidence clearly supported the gradual extinction model, and some thought the evidence was too ambiguous to answer the extinction question either way. The principle of parsimony as employed by vertebrate paleontologists allowed them to continue to support the gradual terrestrial extinction model as a more parsimonious – and therefore, more likely to be true – explanation than the impact hypothesis, even in the face of ambiguous fossil evidence.

Walter Alvarez, suprisingly, agreed that the terrestrial extinction model was the more parsimonious one, but also expressed his belief that the evidence in this case clearly favoured the less parsimonious hypothesis (i.e., the impact hypothesis). Finally, Dale Russell used a different approach in his defense of the impact hypothesis; he argued that the invocation of terrestrial extinction causes was not in fact more parsimonious, but only 'less astonishing' than the impact hypothesis. Taken together, these examples show how the principle of parsimony, seemingly a straightforward rule in the practice of science, can be used in many different ways to support and argue against the same theory.

3) Impact Theory was too Reductionistic

The issue of parsimony is even more complex than described above, because at the same time that some vertebrate paleontologists were rejecting the Alvarez hypothesis because it was not the simplest explanation for the mass extinction, other vertebrate paleontologists derided it for being too simple. This apparent contradiction resulted from the recognition that while parsimony was a valid principle and should be upheld wherever possible, some questions in geology and biology were too complex to be explained by simple solutions. Extinction in particular was one of these complex questions, as stated by David M. Raup: "extinction is seen as a rather ordinary phenomenon, but one that is complex and not amenable to simple explanations."[261] Paleontologists seemed to believe, although few of them consciously examined and articulated this belief, that while parsimony was a desirable goal in paleontology, reductionism was not. The idea that reductionism was not universally applicable constituted a fundamental methodological and theoretical rift between the physical sciences and the historical sciences.

Astrophysicist Richard A. Muller, a friend of Luis and Walter Alvarez, wrote about Walter's sympathy for the complexities of paleontology:

> Walt was more sympathetic to the paleontologists than Luie was. Geology [Walter's field] had much more in common with paleontology. Not only did both sciences make extensive use of fossils, but they both had to handle complex data and complex phenomena. Unlike physics [Luis's field], these fields rarely had simple explanations to account for their observations.[262]

Several scientists have recognized that while reductionism is a valued principle in the physical sciences, including physics and chemistry, it is less valuable in or perhaps even not applicable to the historical sciences, including geology, paleontology, and evolutionary biology. For example, geologist Cameron J. Tsujita wrote:

> The geological sciences, dealing with complex natural systems, are ultimately influenced by components of physics, chemistry, and biology, which are dictated by the principles of parsimony. Perhaps subconsciously, geoscientists apply parsimony to geological problems despite their awareness that natural systems do not always operate in a simple manner.[263]

Raup also stated that most paleontologists felt reductionism was not an appropriate goal in the understanding of mass extinctions:

> Mass extinctions are very complex affairs and are the result of many intricate interactions among organisms and between organisms and their environment. A simple explanation for such a complex event as the Cretaceous extinction is inappropriate and likely to be wrong.[264]

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[261] David M. Raup, "Death of species," in Matthew Nitecki, ed., *Extinctions* (Chicago and London: University of Chicago Press, 1984), 15.
[262] Muller, *Nemesis, the Death Star*, 71.
[263] Tsujita, "The significance of multiple causes and coincidence in the geological record," 271-272.
[264] Raup, *Nemesis Affair*, 70-71.

Evolutionary biologist and philosopher of biology Ernst Mayr wrote extensively about the concept of reductionism and why it could not be applied in evolutionary biology.[265] Reductionism, simply stated, is the idea that any physical process or system, no matter how complex, can be completely understood by breaking it down into its most fundamental units, and applying to them the basic mathematical, physical and chemical laws of the universe. Physicists, of all scientists, embrace reductionism most enthusiastically, and many scientists believe that physics is that science to which all other sciences ought to be reducible.

In the biological sciences, however, things are not so simple. Mayr has identified several kinds of reductionism, only one of which, in his opinion, can and should be applied to the biological sciences. The first kind is constitutive reductionism, which simply states that living organisms are made of the same physical matter and therefore obey the same physical and chemical laws as inanimate objects. Modern biologists and paleontologists do not dispute this kind of reductionism.[266] Mayr also described explanatory reductionism, which he believed was an erroneous and unnecessary attempt to force biology to conform to physics.[267] Explanatory reductionism is the idea that one can understand the whole merely by examining its parts. This idea seems to work in physics, but cannot be applied to biology, because of the property of emergence. One cannot understand everything about an organism just by examining the cells it is made of – one will learn some things about how it works, but this type of analysis reveals nothing about its mating habits or social behaviours, for example.[268] Because of his view against this second type of reductionism, Mayr also inverted the traditional concept of the hierarchy of the sciences: biology, he stated, is in fact more inclusive than and thus superior to physics. Mayr supported this statement by quoting George Gaylord Simpson, who said "all known material processes and explanatory principles apply to organisms,

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[265] Ernst Mayr, *The Growth of Biological Thought: Diversity, Evolution and Inheritance* (Cambridge and London: The Belknap Press of Harvard University Press, 1982).
Ernst Mayr, *Toward a New Philosophy of Biology: Observations of an Evolutionist* (Cambridge and London: Harvard University Press, 1988).
Also see following article based on interview with Mayr: Roger Lewin, "Biology is not postage stamp collecting," *Science* vol. 216, no. 4547 (May 14, 1982): 718-720.
[266] Mayr, *The Growth of Biological Thought*, 60.
[267] *Ibid.*
[268] *Ibid.*, 62-63.

while only a limited number of them apply to non-living systems. Biology, then, is the science that stands at the center of all science."[269]

It is not clear how many paleontologists have read Mayr's work on the fallacies of reductionism,[270] but they certainly appear to agree with his views on the subject. Over and over, in their articles, books, interviews, and personal communications, vertebrate paleontologists insisted that the impact theory was too simple a solution for the complex problem of mass extinction. Indeed, William A. Clemens, the most vocal anti-impactor among vertebrate paleontologists, even said:

> I think [the] major contribution [of vertebrate paleontologists to the impact/extinction debate] has been to tenaciously resist the innate reductionism of physical scientists and to keep posing pertinent paleobiological questions.[271]

Sociologist of science (and daughter to William Clemens) Elisabeth A. Clemens has written a few articles on the impact/mass extinction debate, and noted in one that "The tension between biological complexity and geological imprecision on the one hand, and astrophysical simplicity on the other, has been avoided rather than resolved."[272] This 'tension' has not been commented on by many authors, and does not appear to have been recognized by many of the players. Interestingly, Raup appears to be the only paleontologist who has recognized the apparent contradiction in dismissing the Alvarez hypothesis as simultaneously too simple and not simple enough. Raup contended that neither argument evaluates the actual scientific validity of the hypothesis proper and its predictions, and concluded:

> In my experience, about as many people say, 'Scientific problems rarely have simple answers,' as say, 'Where there is a choice, simple explanations are most likely to be correct.' Both statements are rhetorical rather than analytical, and one hates to see them used as arguments for or against a theory.[273]

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[269] George Gaylord Simpson, qtd. in Mayr, *The Growth of Biological Thought*, 35.
[270] Mayr is a founder of evolutionary biology and has been deeply influential in biology and paleontology. It is likely that most vertebrate paleontologists have read Mayr's scientific textbooks, if not his philosophical writings. However, I did not encounter a single reference to Mayr, even by vertebrate paleontologists who argued that their science was too complex to be explained by simple hypotheses like the impact theory, and that physicists and impact supporters were too reductionistic.
[271] William A. Clemens, response to VRTPALEO Listserver Survey, January 2, 2003.
[272] Elisabeth Clemens, "Of asteroids and dinosaurs," 431-432.
[273] Raup, *Extinction: Bad Genes or Bad Luck?* 92-93.

As with the vertebrate paleontologists' employment of the principle of parsimony, their invocation of biological complexity seems in part to be a rhetorical device brought in to argue against a theory to which they objected on other grounds. Notwithstanding this possibility, the evidence of the vertebrate fossil record did indeed present a more complex picture than some impact supporters realized, as we shall see later in this chapter.

Social Grounds For Rejecting the Alvarez Hypothesis

In addition to the above theoretical reasons, there were also several social reasons why vertebrate paleontologists rejected the Alvarez impact hypothesis. These social reasons were usually not discussed openly in scientific publications, but did come out in interviews and less formal publications, such as popular accounts of the impact debate, and responses to the survey I posted on the VRTPALEO Listserver. Although vertebrate paleontologists did not reject the Alvarez hypothesis solely on the basis of the following social factors, these factors did predispose vertebrate paleontologists to react negatively towards both the impact theory itself and the Alvarez team as well. In combination with the ambiguity of the vertebrate fossil evidence, and the several theoretical presuppositions which made the impact theory seem improbable, the following negative social factors were one more reason to view the impact hypothesis skeptically.

1) The Perceived Hierarchy of Sciences

A major barrier to communication between the Alvarez team, composed primarily of physical scientists, and vertebrate paleontologists was the perception on both sides of a hierarchy of scientific disciplines. Several participants in this debate described this hierarchy, but the most succinct description is possibly the following, by physicist, astronomer, and geologist Robert Jastrow:

> I remember once being told… that an intellectual hierarchy exists in science, with mathematics and theoretical physics on the top, experimental physics just beneath and then, further down, chemistry and perhaps astronomy. Geology and paleontology, which deal with dirty objects like rocks, are considerably lower on the list, and biology – at least the parts that deal with soft, squishy things like entire organisms – is at the bottom.

... The trouble with this hierarchy is that a physicist's methods only work well on physics problems – precise, well-defined, capable of a mathematical formulation. Perhaps the experts on ancient plant and animal life didn't know much math, but they knew their fossils, and the fossils told them Alvarez was wrong.[274]

For some scientists, most notably Luis Alvarez, a belief in the validity of this hierarchy led to a belief in the scientific superiority of physicists (and other physical scientists) and a belief in the scientific inferiority of paleontologists. Acceptance of this hierarchical distribution of sciences also led to differences in methodology and standards of evidence, and also coloured scientists' perceptions of other scientists from other disciplines. Walter Alvarez published two articles calling for a replacement of the scientific hierarchy with a less judgmental scientific 'spectrum', but his argument only served to highlight his commitment to the hierarchical standard, as we saw in Chapter 2.

William Glen has argued that the most relevant application of the scientific hierarchy to the reception of the impact theory in the Earth sciences is that field's long history of struggling against the evils of 'intruders' from higher up on the scientific ladder.[275] These intruders or 'disciplinary aliens' attempted to appropriate and solve problems in the lesser sciences beneath them, and (as Glen stated) history shows the intruders have in most cases turned out to be wrong.[276] Glen's chief example in his book on *The Mass-Extinction Debates* is the classic story of Lord Kelvin's estimate of the age of the Earth.[277] Kelvin, a well-respected physicist, argued that the Earth could not be as old as Hutton and Lyell's uniformitarianism demanded. If one assumed, as Kelvin did, that the Earth had started out in a molten state and had cooled steadily to its present temperature, then reverse calculations only allowed an age of 20 to 40 million years for the Earth. Because of what Glen calls Kelvin's "magisterial authority," his conclusions were reluctantly accepted, even though geologists and paleontologists knew that the changes they saw preserved in the rock and fossil record revealed that the Earth had a much longer history.[278] It was eventually shown that radioactive decay has acted to heat

[274] Jastrow, "The Dinosaur massacre: a double-barreled mystery," 52.
[275] Glen, "How science works in the debates," 80.
[276] Glen, "A manifold current upheaval in science," 195.
[277] Glen, "How science works in the mass-extinction debates," 80.
[278] *Ibid.*, Glen wrote that the term 'magisterial authority' was actually coined by S. Toulmin.

the interior of the Earth, and the assumption that it has been cooling steadily since its formation was incorrect. The uniformitarians were eventually vindicated; but such was Kelvin's position as a respected authority in the highest scientific field, physics, that his calculations were accepted over the evidence of the fossil record.[279]

Glen's argument, therefore, is that because of this history of disciplinary outsiders – particularly physicists – invading the earth sciences and forcing incorrect pronouncements upon them, earth scientists were predisposed to both resent the Alvarez team's intrusion into their field and to assume the impact theory was probably wrong. While I agree with Glen that Earth scientists may have held these predispositions, I believe that – at least in the specific case of the vertebrate paleontologists – these particular predispositions of resentment and negativity arose more out of a sense of territorialism than as a reaction to the perceived hierarchy of sciences. I will elaborate on this point in the next section, which discusses territorialism in detail.

The perceived hierarchy of sciences also came into play in the continental drift debate of the early 20th century. Geophysicists initially objected to continental drift, arguing that it is physically impossible for the continents to plow through oceanic crust, as Wegener proposed. Continental drift, in its modern guise of plate tectonics, was finally accepted, however, after geophysicists proved the occurrence of sea-floor spreading. Invertebrate paleontologist Derek Ager scoffed at how geophysicists at all stages of the debate looked down upon geologists, their more historically- and less physically-oriented colleagues: "I remember the time when the poor innumerate geologists were enthusiastic about continental drift, but the geophysicists said that it was impossible (now they claim all the glory)."[280]

Ager's example highlights a particular manifestation of the scientific hierarchy: the value placed on mathematical and computer modeling by scientists at opposite ends of the hierarchy. The physical sciences, at the top of the totem pole, tend to be quite reductionistic and amenable to simple solutions. The problems typical of physics and chemistry can be mathematically modeled, and most physical scientists seem to agree that such models produce useful and reasonably accurate representations of the real

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[279] Glen, "How science works in the debates," 80.
[280] Ager, *The New Catastrophism*, 167

world. Their ability to generate and use mathematical and computer models also make the physical sciences seem more precise and quantifiable, and therefore more scientific, than the historical sciences. Such modeling is therefore valued highly in the physical sciences.[281]

The historical sciences, at the other end of the hierarchy, typically are not easily reducible, and rarely break down into simple cause-and-effect relationships (as discussed in the previous section on reductionism). Often in geology, paleontology, and evolutionary biology, and in history itself, there are so many interrelated factors in operation that individual factors cannot be easily identified, nor can their individual effects be easily ascertained. It therefore becomes quite difficult, if not impossible, to apply mathematical and computer models in the historical sciences. Such models require so many simplifying assumptions that many historical scientists doubt whether meaningful results can be produced by such modeling. Vertebrate paleontologist Armand de Ricqles used the following analogy to demonstrate this point:

> [I]n all historical sciences we see that the causation is a complex one and it's circumstantial causation, which probably comes from the fortuitous linkage of several factors which incidentally happen to occur more or less at the same time. You cannot say that the Second World War was caused by precisely one thing.[282]

In physics, it is a good thing if one's theory can be modeled on a computer. Luis Alvarez clearly thought so, as evidenced by his comments in a 1983 article published in the Proceedings of the National Academy of Sciences.[283] Alvarez wrote that it was a computer simulation which convinced him that the impact-generated dust cloud could be spread around the world, and reported his relief that 'the computers got us out of trouble'.[284] Alvarez elaborated proudly:

> The so-called hydrodynamic computer programs used in these computer simulations are like the ones used to design nuclear weapons; they involve

[281] Jastrow, "The Dinosaur massacre: a double-barreled mystery," 50-53, 109.
Elisabeth Clemens, "Of asteroids and dinosaurs," 421-456.
Benton, "Scientific methodologies in collision," 269-294.
[282] Armand de Ricqles, qtd. in Louie Psihoyos and John Knoebber, *Hunting Dinosaurs* (New York: Random House, 1994), 258.
[283] Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 627-642.
[284] *Ibid.*, 636.

> 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 been brought to bear on problems of interest to paleontologists.[285]

This statement clearly demonstrates Alvarez's regard for and confidence in mathematical and physical modeling. Alvarez was also proud of his attempts to use statistics to address the problem of the three-metre gap in Hell Creek, Montana. As discussed briefly in Chapter 3, however, vertebrate paleontologists disagreed with Alvarez's statistical analysis, on the grounds that the assumptions on which he based his statistical model oversimplified and misrepresented the real biological and geological conditions, rendering his conclusions meaningless. For example, J. David Archibald challenged Alvarez's analysis on the grounds that while his statistical analysis assumed dinosaur fossils are distributed randomly throughout the stratigraphic column, this is not in fact true: in reality, a concatenation of biological, taphonomical, sedimentological, and geographical factors produces a non-random distribution.[286] Elisabeth Clemens agreed with Archibald about the inappropriate application of statistical models to the complexities of the fossil record:

> [The three metre gap] is dismissed as nonsignificant on the basis of statistical analyses, 'computer-generated plots of randomly occurring 'fossils',' Monte Carlo methods, and so forth. Yet fossil deposition is neither regular nor random, as assumed by these tests. Echoing the use of 'hydrodynamic computer programs', technical sophistication is employed to dismiss specific findings. This argument, presented as refuting specific empirical evidence, is another case of model-building both in relative independence from the fossil record, and as an attempt to minimize its significance as a record of the history of life – and, therefore, as a source of falsifying evidence.[287]

Vertebrate paleontologist Robert Bakker also scoffed at the attempt of some 'higher' scientists to apply their own quantitative methods to paleontological problems:

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[285] *Ibid.*, 636.
[286] Archibald, *Dinosaur Fossils and the End of an Era*, p. 45-46.
[287] Elisabeth Clemens, "Of asteroids and dinosaurs," 435. Phrases in single quotation marks are paraphrases from Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 638.

> The ignorance of these people is simply unbelievable. They know next to nothing about how real animals evolve, live, and become extinct. But despite their ignorance, the geochemists feel that all you have to do is crank up some fancy machine and you've revolutionized science. ... In effect, they're saying this: 'we high-tech people have all the answers, and you paleontologists are just primitive rockhounds'.[288]

This, then, is perhaps the fundamental problem that the hierarchy of science presented to vertebrate paleontologists in the impact debate: they saw the physical scientists, like Alvarez, as being too reductionistic and relying too much on computer simulation and other models which may or may not mean anything, instead of looking at the "real" evidence: the fossil record.

2) Territorialism, Arrogance, and Explanatory Incommensurability

> Physicists would no doubt cast a jaundiced eye upon the newest theories of quantum physics published by biologists. Yet expert opinion about the demise of the dinosaurs is apparently off-limits to no one.[289]

Territorialism was a factor in this debate in several ways. It created hostility and arguments about where to place the burden of proof; it engendered conflict about who was and who was not qualified to pass judgment on various issues within the debate; and it affected the standards of evidence required of the various theories, disciplines, and players. In particular, the vertebrate paleontologists' innate desire to protect their scientific territory was exacerbated not only by the *fact* of its invasion by physical scientists (such as Luis Alvarez), but by the *manner* in which this invasion was often carried out. Some of the conflict over scientific territory can be attributed to explanatory incommensurability: scientists of different disciplines not only believed different answers but also asked different questions. In many cases, however, the conflict was heightened by the arrogant and cavalier attitudes of some of the players.

As discussed in the introduction, when the Alvarez hypothesis was first proposed paleontologists did not deem that it required a response. Although they believed the question of extinction causes was part of their territory as paleontologists, the particular province of dinosaur extinction had been invaded so often by non-paleontologists, most

[288] Robert Bakker, qtd in Officer and Page, *The Great Dinosaur Extinction Controversy*, 78.

of whom espoused such non-scientific and patently absurd theories, that vertebrate paleontologists had adopted a procedure of simply ignoring crackpot ideas and waiting for them to go away. But the impact hypothesis, unlike its many predecessors, did not go away. It captivated the attention of scientists, the media, and the public, all of whom were suddenly talking about what had killed the dinosaurs… but none of whom were investigating the actual paleontological evidence surrounding the dinosaurs' demise.

In virtually every paper written by Luis and Walter Alvarez, for example, it is clear that for them, the impact was the priority, the most important issue, while its effects, including the mass extinction that the impact might or might not have caused, were secondary. The question the Alvarez team asked was: Was there an impact at the end of the Cretaceous period, and what were its effects? The framing of the question in this particular way affected every other statement and argument made by the Alvarez team.[290] Whenever they talked about 'the mass extinction', for example, this clearly referred to 'the extinctions caused by the impact'. At first, the Alvarez team argued that all of the end-Cretaceous extinctions were caused by the impact. When paleontologists responded that some of the extinctions had occurred gradually and/or preceded the impact, the Alvarez team dismissed these particular extinctions as unimportant or irrelevant.[291] This dismissal is perfectly understandable from an impact supporter's point of view: if the question was what were the effects of impact, then any extinctions that preceded the impact could not have been caused by it and were clearly irrelevant.

Paleontologists could not understand or condone this dismissal of prior/gradual extinctions because they were concerned with a completely different question – and these extinctions *were* relevant to their question. The question paleontologists were asking was: What was the pattern of extinctions at the end of the Cretaceous period, and what cause or causes created this pattern? When the question was framed this way, all of the extinctions that occurred at or near the end of the Cretaceous period became not only equally important, but interrelated. There was a mass extinction, of many species. It is possible that some extinctions resulted from one cause, while other extinctions were the

[289] Archibald, *Dinosaur extinction and the End of an Era*, 12.
[290] Refer to my discussion of Walter Alvarez's 'spectrum' of sciences in Chapter 2.

result of a totally different cause, but for paleontologists, the question involved the end-Cretaceous biosphere as a whole, and it made no sense to focus on only some of the extinctions and ignore the pattern, the big picture.

The most hotly contested territory in this debate was the extinction of the dinosaurs. As stated above, the Alvarez team and other impact supporters eventually came to accept that some of the end-Cretaceous extinctions could not be attributed to the bolide impact, and even managed to use this acceptance to strengthen their own theory, by dismissing these other extinctions as irrelevant or background events.[292] They did not accept, however, that the extinction of the dinosaurs in particular might have been caused by gradual, terrestrial factors instead of impact. As discussed in the Introduction and Chapter 3, from its very inception the impact debate has been hinged on the fate of the dinosaurs, and the impactors did not want to give up their poster child to the gradualists. Aside from the fact that the actual fossil record of the dinosaurs did not support impact as an extinction mechanism, vertebrate paleontologists vehemently opposed this appropriation of their scientific territory by outsiders who not only knew little or nothing about the dinosaurs, but didn't seem to feel they needed to know anything about them.

From the beginning of the debate, the Alvarez team and various other impact supporters have made sweeping, general statements about having 'solved' the extinction of the dinosaurs, without first actually examining the evidence of the dinosaur fossil record. Walter Alvarez, for example, wrote in his popular account of the impact debate: "*We know today what killed the dinosaurs* because of Frank Asaro's ability to make these remarkable measurements."[293] The Alvarez team also seemed quite unconcerned about their lack of paleontological expertise, as illustrated by the following statement made by Luis Alvarez (also discussed briefly in Chapter 2):

> All of us [on the Alvarez team] 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 dinosaur)

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[291] Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 628.
[292] Elisabeth Clemens, "Of asteroids and dinosaurs," 441.
[293] Walter Alvarez, *T. rex and the Crater of Doom*, 68 (Emphasis added).

> skull on one occasion. So, we have not 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.[294]

Alvarez appeared to be suggesting that because of a few minor forays that his team – and one team member's husband – made into areas containing geological and paleontological specimens, they had proven their contemplation of – and therefore competence in? – 'all phases of the subject'. Their supposed expertise included the field of vertebrate paleontology, as suggested by the *Triceratops* reference. It is not surprising that vertebrate paleontologists were offended by such cavalier statements. Would a weekend visit to a nuclear accelerator – by a paleontologist or a paleontologist's spouse – allow that paleontologist to make pronouncements on the subject of particle physics? Vertebrate paleontologists objected to the arrogance and superiority evidenced by such comments. The situation was not improved by the various disparaging comments made by Luis Alvarez about vertebrate paleontologists and other impact detractors. As discussed in Chapter 2, Alvarez publicly impugned Clemens's scientific qualifications and dismissed vertebrate paleontologists as nothing more than stamp collectors. Most vertebrate paleontologists did not think the scientific evidence leaned in favour of the impact hypothesis, and the insults flung at them by its staunchest supporter did nothing to change their minds.

The objections of paleontologists to the impact hypothesis led some impact supporters to accuse paleontologists of erecting "straw men" to object to. Graham Ryder of the Lunar and Planetary Institute contributed a paper on the historical context and burden of proof in the impact debate to the proceedings of Snowbird III.[295] Ryder stated that "The impact hypothesis… in no way requires that all or even most of the upper Maastrichtian extinctions resulted from the impact." He accused impact detractors of attributing the following incorrect corollaries to the impact hypothesis: that all or nearly all of the end-Cretaceous extinctions must have been caused by impact; that all of these extinctions occurred instantaneously and globally; and that impact would produce a

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[294] Luis Alvarez, "Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago," 627.

random, universally devastating pattern of destruction (which does not match the observed selectivity of extinctions). But, Ryder continued, the impact hypothesis does not actually demand any of these things:

> There is an unnecessary polarization of concepts: that either extinctions are not related to an impact or that all extinctions are related to an impact. In reality, some extinctions could precede and be unrelated to an impact, others could be an almost direct or near-term result of impact effects such as atmospheric heating or darkness, and others could be slower responses, perhaps over a few years to many tens of thousands of years, to a dramatically changed environment that is still in biotic instability.

Ryder is correct in all of these points: it is true that causing all of the extinctions, causing all of the extinctions instantaneously, and causing non-selective extinctions are not logically necessary corollaries of the impact hypothesis *in theory*. There is also some foundation for his allegations; William Clemens in particular made such unreasonable demands of the impact hypothesis, at least in his initial publications on the subject (as discussed in Chapter 3). However, Ryder has missed the real point: whether these corollaries are necessary or not, the fact is, the majority of impact supporters claimed that they were true. The Alvarez team and some of their colleagues have referred throughout their publications to the impact which caused *the* mass extinction (not some of the extinctions).[296] Again, in these publications and elsewhere, the K-T mass extinction was described as having occurred instantaneously or rapidly, not (even in part) gradually.[297] Impact supporters also consistently failed to acknowledge, much less discuss or attempt to explain, the complex pattern of extinction and survival among the various groups at the K-T boundary, much to the disgust of paleontologists, who viewed this pattern as the ultimate evidence on which the extinction question must finally be settled.[298]

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[295] Graham Ryder, "The unique significance and origin of the Cretaceous-Tertiary boundary: historical context and burdens of proof," in Ryder, Fastovsky, and Gartner, eds., *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History*, 31-38.
[296] See for example:
Luis Alvarez et al, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," 1095-1108.
Luis Alvarez, "Chapter 15: Impacts and extinctions," in *Alvarez: Adventures of a Physicist*, 251-267.
Walter Alvarez, *T. rex and the Crater of Doom*, x, 15.
Muller, *Nemesis, the Death Star*, 3, 69-70.
[297] See for example:
Walter Alvarez, *T. rex and the Crater of Doom*, 3-18.
Luis Alvarez, *Alvarez: Adventures of a Physicist*, 250.
[298] William Clemens, "Evolution of the terrestrial vertebrate fauna," 63-64, 78.

The vertebrate paleontologists and the impact supporters were thus placed in a stalemate: vertebrate paleontologists admitted that an impact had occurred and that it may have contributed to the K-T mass extinction, but they did not believe that terrestrial vertebrates in general and dinosaurs in particular had been exterminated by the asteroid. Impact supporters, on the other hand, conceded that some groups, such as inoceramid and rudist bivalves, had gone extinct before the impact, and even allowed that terrestrial factors like volcanism and climate change might have contributed to the K-T mass extinction, but they continued to insist that the dinosaur extinction in particular had been caused by the bolide impact.[299] The conflict would not be settled unless vertebrate paleontologists abandoned their territory or impact supporters accepted the primacy of paleontological evidence as an arbiter of the debate.

3) Prior Commitment to Other Theories

The prior commitment of the various participants in the impact debate to other relevant theories has also conditioned their acceptance or rejection of the Alvarez impact hypothesis.[300] William Glen found, in his analysis of the debate, that with only one (unnamed) exception, every scientist who had published on or publicly endorsed a gradual, endogenous extinction theory pre-Alvarez continued to support this same theory even after the Alvarez team proposed their impact hypothesis.[301] Glen also noted that those scientists who already supported other theories distinct from the impact theory but compatible with or supported by it were more likely to support the impact theory when it arose. This point can be succinctly illustrated by the example of invertebrate paleontologists Stephen Jay Gould and David M. Raup. Gould's punctuated equilibrium model and Raup's work on the qualitative differences between background extinctions

[299] Ward, *The End of Evolution*, 150. Ward wrote: "Many scientists began to believe that yes, perhaps a meteor had hit the earth, but no, its impact had nothing to do with the extinctions occurring about that time. Luis Alvarez would have none of this. His tactic was to simply denigrate the methodology of paleontology and personally insult those paleontologists most critical of his theory. … Alvarez took his attack beyond all bounds of scientific decency, calling Clemens 'generally incompetent' and others far worse."
[300] Glen, "How science works in the debates," 49-50.
[301] Glen, "A manifold current upheaval in science," 202.

and mass extinctions were both entirely compatible with the punctuational, random event described by the impact model. As Gould stated in an interview with William Glen:

> I only remember Dave Raup and myself as being strongly favorable [to the Alvarez theory]. ... Dave liked it because he was interested in random processes; I liked it because I'm interested in punctuational processes. In other words, we had predisposing biases that made us look upon Alvarez favorably.[302]

It is not easy to find examples of vertebrate paleontologists with prior published commitments to any extinction models, gradual or catastrophic, since it had become so unfashionable for paleontologists to seriously discuss the subject of extinction.[303] One example does stand out, however: the case of Dale Russell (discussed in Chapter 3). Russell was the only vertebrate paleontologist to immediately embrace the impact hypothesis, and was likewise the only one who had a prior commitment to a catastrophic, extraterrestrial model of extinction. The impact hypothesis likely appealed to Russell for the same reasons that the supernova model, to which he was previously committed, had: both extinction hypotheses were compatible with his beliefs that the dinosaurs were evolutionarily successful, potentially highly intelligent creatures, that had gone extinct abruptly and for reasons outside of normal selective pressures.

Other vertebrate paleontologists, who had not previously endorsed a catastrophic extinction model, and who retained a number of theoretical commitments incompatible with such models,[304] were not predisposed to view the impact hypothesis favourably when it was proposed.

Scientific Grounds for Rejecting the Impact Hypothesis

The impact hypothesis was subject to more rigorous scientific testing than any other mass extinction hypothesis ever proposed. In large measure this was because the Alvarez hypothesis was the first truly testable example of such hypotheses. Most of this scientific testing, however, revolved around searching for and evaluating evidence of the impact itself, not its connection (if any) to the K-T mass extinction. For example, some

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[302] Stephen Jay Gould, "On the mass-extinction debates: an interview with Stephen Jay Gould, conducted and compiled by William Glen," in Glen, ed., *The Mass-Extinction Debates*, 256-257.
[303] See Introduction.

scientists attempted to invoke an endogenous source for the iridium anomaly, such as biogenic concentration or volcanic eruption. Physical markers of impact, such as tektites, shocked quartz, ratios of other siderophile elements besides iridium, tsunami deposits, and several candidate impact craters, were debated hotly through the 1980s and 1990s. For the most part, however, these battles were fought by geologists, chemists, physicists, and astronomers.[305]

Vertebrate paleontologists in many cases did not feel qualified to pass scientific judgment on the evidence for impact itself, and most agreed or came to agree that the evidence seemed to indicate that one or more bolide impacts had indeed occurred at the end of the Cretaceous period.[306] Proving an impact had occurred, however, was not the same thing as proving the impact had caused the K-T mass extinction – a point that paleontologists often felt other scientists had missed. Vertebrate paleontologists did feel qualified to examine and evaluate what they regarded as the only definitive source for evidence on the cause of the mass extinction of vertebrates at the K-T: the geological and fossil record spanning the Cretaceous-Tertiary boundary.[307] From this evidence,

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[304] Discussed above, this chapter.
[305] See for example:
Bruce F. Bohor, E. E. Foord, P. J. Modreski, and D. M. Triplehorn, "Mineralogical evidence for an impact event at the Cretaceous-Tertiary boundary," *Science* vol. 224, no. 4651 (May 25, 1984): 867-868.
Charles B. Officer and Charles L. Drake, "The Cretaceous-Tertiary transition," *Science* vol. 219, no. 4591 (March 25, 1983): 1383-1390.
Joanne Bourgeois, Thor A. Hansen, Patricia L. Wiberg, and Erle G. Kauffman, "A tsunami deposit at the Cretaceous-Tertiary boundary in Texas," *Science* vol. 241, no. 4865 (July 29, 1988): 567-570.
Robert D. Brooks, Roger D. Reeves, Xing-Hua Yang, Douglas E. Ryan, Jiri Holzbecher, John D. Collen, Vincent E. Neall, and Julian Lee, "Elemental anomalies at the Cretaceous-Tertiary boundary, Woodside Creek, New Zealand," *Science* vol. 226, no. 4674 (November 2, 1984): 539-542.
[306] Carroll, *Vertebrate Paleontology and Evolution*, 327.
Raup, "Biological extinction in Earth history," 1531.
Leigh M. Van Valen, "Catastrophes, expectations, and the evidence," (Review of *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, eds. Leon T. Silver and Peter H. Schultz) *Paleobiology* vol. 10, no.1 (1984): 143.
Vertebrate paleontologists Sarjeant and Currie present the physical and geochemical evidence for and against impact at the beginning of the following paper, but this evidence is taken from other published papers, not their own research, and is not itself evaluated by Sarjeant and Currie but rather forms the background to their discussion of the K-T mass extinction:
Sarjeant and Currie, "The 'Great Extinction' that never happened," 239-247.
Sociologist Elisabeth Clemens also notes that participants in the impact debate tended to focus on that evidence which fell within their own discipline:
Elisabeth Clemens, "Of asteroids and dinosaurs," 432.
[307] See for example:
Archibald and William Clemens, "Mammal evolution near the Cretaceous-Tertiary boundary," 339.

vertebrate paleontologists summoned several criticisms of Alvarez theory. Although one might make a case for splitting these criticisms into more categories, I present only two. The first deals with evidence from mass extinctions and impact horizons in general, including but not limited to the Cretaceous-Tertiary. The second category includes all of the objections raised by vertebrate paleontologists based on the specific evidence surrounding the K-T mass extinction in particular. I have chosen to group all of the latter objections together in order to more easily demonstrate the interplay and inconsistencies between them.

1) Lack of Correspondence Between Known Mass Extinctions and Known Impacts

Vertebrate paleontologists have studied more mass extinctions than just the K-T, which was the sole or primary focus of many of the impact supporters, at least before the periodicity hypothesis. The Permian-Triassic extinction, which took place approximately 230 million years ago, was much more severe than the K-T: it has been estimated that up to 96% of species went extinct during the former, while only 50% to 75% of species went extinct during the latter.[308] The end-Permian, like the end-Cretaceous, was also a time of massive volcanism (the eruption of the Siberian Traps in Russia) and an extensive regression of the sea. It appears then, that the two greatest episodes of mass extinction in Earth history coincided with times of intense volcanism and a dramatic lowering of sea level. In contrast, there is as yet no evidence of a bolide impact at the end of the Permian period. While some impact supporters claimed to have found several iridium anomalies at various levels throughout the fossil record, and while some scientists argued that both extinction rates and cratering rates show a periodicity of 28 to 32 million years, the only mass extinctions that have been associated with a high degree of certainty to iridium anomalies and impact craters are the K-T and the Eocene-Oligocene, approximately 35 million years ago.[309] When vertebrate paleontologists compare events in the fossil record, then, instead of just focusing on the K-T boundary in isolation, they have tended

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William Clemens, "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," 78.

308 Archibald, "I. Extinction, Cretaceous," 222.

309 David Jablonski, "Causes and consequences of mass extinctions: a comparative approach," in David K. Elliott, ed., *Dynamics of Extinction* (New York: John Wiley & Sons, Inc., 1986), 195.

to see a larger pattern at work in the causes of mass extinctions; they have also seen numerous examples of extinctions without impacts, and impacts without extinctions. As paleontologist Norman MacLeod wrote:

> Since a number of large impacts have occurred without causing associated local or global mass extinctions,... and since evidence exists for major extinction events that do not appear to have been driven by bolide impact,... alternative extinction mechanisms compatible with prolonged or progressive extinction patterns... remain viable explanations (in whole or in part) for aspects of the K/T event.[310]

Similarly, Clemens, Archibald, and Leo J. Hickey wrote in their 1981 *Paleobiology* article "no evidence from any time in earth history conclusively links the collision of extraterrestrial objects with major changes in the patterns of evolution or extinction."[311] Vertebrate paleontologist Robert L. Carroll agreed, in his 1988 textbook on *Vertebrate Paleontology and Evolution*, that it is difficult to explain "the lack of great extinctions at the other times when craters 100 kilometres or more in diameter are known to have been formed," and pointed out that "Iridium anomalies have been discovered at other horizons that are not associated with mass extinctions, and are missing from other horizons, such as the Permo-Triassic boundary, when there were mass extinctions."[312]

Many impact supporters found it ludicrous to imagine that the explosive impact of a 10-kilometre asteroid and the K-T mass extinction could have occurred at very nearly the same time without the former being the cause of the latter; this concatenation of events simply could not be a coincidence. Luis Alvarez wrote in his bibliography:

> I am unable to take seriously Bill [Clemens]'s notion that the dinosaurs, after ruling the world for 140 million years, suddenly and for no particular reason disappeared just 20,000 years before the greatest catastrophe ever known to have been visited upon the earth.[313]

This does seem like an unreasonable coincidence when read in Alvarez's phrasing, but upon closer examination, it can be seen that he has misrepresented what Clemens was asserting. Clemens (and the other gradualist paleontologists) did not maintain that dinosaurs vanished "suddenly and for no particular reason"; they marshaled evidence

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310 MacLeod, "K/T Redux", 312.
311 William Clemens, Archibald, and Hickey, "Out with a whimper not a bang," 297.
312 Carroll, *Vertebrate Paleontology and Evolution*, 327.

showing that dinosaurs declined in diversity for several years before finally becoming extinct, and several plausible reasons for this decline and extinction have been proposed, the strongest of which is arguably Archibald's regression and habitat fragmentation model.[314]

Other scientists have pointed out that rare coincidences can in fact be expected, when one is examining a span of time as immense as the entire fossil record.[315] If, for example, an event occurs so rarely that the chance of it happening in any given year is only one in six hundred million, we would probably feel justified in dismissing it as highly improbable. But improbable does not mean impossible, and when one takes into account the fact that the known fossil record spans more than a billion years, there is in fact a 100% probability that this one-in-six-hundred-million event has occurred at least once. It does indeed seem like an extraordinary coincidence that one of the largest known bolide impacts, one of the largest known episodes of volcanism, and one of the greatest regressions of sea level known should all have occurred at roughly the same time, and that all may have contributed to the mass extinction which also occurred at that time. But the theory of the 'rare event' shows that given time enough, such coincidences are bound to occur. Geologist Cameron J. Tsujita also suggested that it might be particularly appropriate to attribute an unusual event such as the K-T mass extinction to a concatenation of causes: "It is readily apparent that events that are rare, within the scales in which they are generally studied, may have origins considerably more complex than those that might first appear."[316] For this reason, Tsujita argued that it makes more sense to approach the K-T mass extinction from a multicausal, rather than a unicausal, perspective.

Walter Alvarez has provided an interesting, if unintentional, glimpse of how the idea of coincidence can be appropriated differently according to the argument one wishes to make. As discussed above, his father felt that because the K-T mass extinction and the

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[313] Luis Alvarez, *Alvarez: Adventures of a Physicist*, 260.
[314] See Chapter 3.
[315] See for example:
Peter E. Gretener, "Reflections on the 'rare event' and related concepts in geology," in Berggren and Van Couvering, eds., *Catastrophes and Earth History: The New Uniformitarianism*, 77-89.
Victor Clube and Bill Napier, *The Cosmic Serpent: A Catastrophist View of Earth History* (New York: Universe Books, 1982), 94.

iridium anomaly marking a bolide impact had occurred so close to each other in time, their juxtaposition could not be a coincidence but must reflect a cause-and-effect relationship. Walter Alvarez, on the other hand, wrote in his 1997 book: "*I would have dismissed the apparent age match between the Deccan Traps and the KT impact-extinction event as a strange coincidence*, if it were not that a second such coincidence [the Siberian Traps and the Permian-Triassic extinction] has turned up."[317] Two things can be deduced from this statement: one, if not for the further evidence provided by the Siberian Traps and the Permo-Triassic extinction, Walter Alvarez would have accepted the temporal juxtaposition of two such unusual events as the second-largest episode of basalt volcanism and the second-largest mass extinction as merely coincidental; and two, as evidenced by the second part of his statement, Alvarez continued to conflate the K-T mass extinction with the bolide impact a priori, as the Alvarez team had done from the beginning, instead of treating their relationship as something which must be (or even had been) proved. Alvarez's statement thus begs the question: if the Deccan Traps might have formed at the same time that the K-T mass extinction took place purely by coincidence, why must the bolide impact have caused, and not merely also coincided with, the mass extinction?

The contradiction inherent in Alvarez senior versus Alvarez junior's comments on coincidence shows that it is a fallacy to assume the K-T mass extinction must have been caused by the bolide impact merely because they occurred at or near the same time. The evidence that there have been other impacts without associated extinctions, and other extinctions without associated impacts, further supported the vertebrate paleontologists' assertions that the cause of the mass extinction could only be proved by an examination of the extinction evidence – in other words, by an examination of the fossil record.

2) The Evidence of the Vertebrate Fossil Record

Although the end of the Cretaceous period did seem to be marked by an unusually high level of extinction, vertebrate and invertebrate paleontologists alike had long recognized that this mass extinction seemed to have begun several million years before

[316] Tsujita, "The significance of multiple causes and coincidence in the geological record," 287.
[317] Walter Alvarez, *T. rex and the Crater of Doom*, 143 (Emphasis added).

the K-T boundary, and was not an instantaneous event. Among invertebrate taxa, inoceramid and rudist bivalves became extinct well below the K-T,[318] and most vertebrate paleontologists agreed that terrestrial vertebrate extinctions, most notably of the dinosaurs, had also begun several million years before the K-T boundary and had proceeded gradually. Several vertebrate paleontologists used the evidence of prior and/or gradual extinction specifically to refute the causal connection between a bolide impact and terrestrial extinctions.[319] For example, Clemens and Archibald, and other vertebrate paleontologists who studied the latest Cretaceous North American dinosaur fossils, have presented two main reasons for their support of a gradual dinosaurian extinction model: evidence of declining dinosaur diversity, and the infamous three-metre gap. Clemens, Archibald, and other vertebrate paleontologists have also argued that the selectivity of the K-T extinctions – which species were exterminated, and which survived – cannot be explained by the impact hypothesis. In this section, I present these arguments of vertebrate paleontologists in detail, and contrast them with a conflicting view of the vertebrate fossil record also held by vertebrate paleontologists. Many of the paleontologists who argued that the vertebrate fossil record supported a gradual endogenous, not catastrophic extraterrestrial, extinction model simultaneously presented the incompatible belief that the evidence of the vertebrate fossil record was too limited, in terms of time resolution, geographic area, and fossil density, to provide clear support for any extinction model. I conclude this chapter with a discussion of the reasons why some vertebrate paleontologists – including William Clemens and J. David Archibald – held both of these incompatible beliefs.

As discussed above,[320] the most contested extinction pattern in the impact/mass extinction debate was that of the dinosaurs. One of the key ways in which vertebrate paleontologists sought to document the pattern of dinosaur extinction was through diversity analysis. Several paleontologists – including Russell, Sloan et al, Archibald and Bryant, and Sheehan and Fastovsky – conducted such studies, as discussed in Chapter 3;

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[318] MacLeod, "K/T redux," 312.
[319] See for example:
Archibald and William Clemens, "Late Cretaceous extinctions," 383.
Bakker, *The Dinosaur Heresies*, 434-5.
Steven M. Stanley, *Extinction* (New York: Scientific American Books, Inc., 1987), 137.

unfortunately several complicating factors made such analyses difficult to conduct and interpret. The ideal method would be to count the number of dinosaur species alive in each successive interval of time and see if it is increasing, decreasing, or remaining the same. Unfortunately, applying such methodology is not straightforward. One problem is that species-level data are not available for all of the required time units and geographical areas, so scientists have been forced to compare higher taxonomic units, such as genera and families. This coarser analysis can create a misleading picture of changes in diversity, since it is possible for the number of species to fluctuate without affecting the number of genera being counted, and even more likely that the number of genera might fluctuate without changing the number of families present.

Another problem is that the chronostratigraphic units that have been compared are not of the same duration in time, are not of the same extent in area, and do not always contain the same preservational biases. The Cretaceous period lasted approximately 70 million years, from 135 to 65 million years ago (Figure 1). This time interval and the rocks which represent it are broken down further into ages (time units) and stages (the equivalent rock unit). The last age/stage of the Cretaceous is the Maastrichtian, encompassing the last 10 or so million years of the Cretaceous, which is itself broken down into epochs (time units) and the formations (geological units) associated with them. Three of the last epochs in the Maastrichtian are the Judithian (=Judith River Formation), the Edmontonian (=Edmonton Formation), and the Lancian (=Lance Creek Formation). The Lancian epoch is half the length of the previous two, in terms of chronological duration. One cannot therefore simply count the number of dinosaur genera present in the Judithian, Edmontonian, and Lancian epochs and compare the raw numbers: the figure for the Lancian epoch will be artificially low because it is so much shorter than the previous two epochs.

When one also considers that the rocks representing each of these epochs may not be equal in geographical extent – or at least, the *sampled* areas may be unequal – and that their differing sedimentological natures may have favored preservation of dinosaur fossils

[320] See section on Territorialism, Arrogance, and Explanatory Incommensurability, this chapter.

in some rock formations and disfavored it in others, it becomes obvious that discerning dinosaur diversity involves a lot more than just counting dinosaurs.

It is not surprising, then, that several contradictory studies of Cretaceous dinosaur diversity have been published. In 1967, Dale Russell published a genus-level diversity analysis based on a survey of previously collected North American dinosaur fossils.[321] Likewise, in 1975, Russell conducted what he called a rarefaction analysis, to compensate for the differential preservation between different rock formations.[322] Russell concluded that dinosaur diversity had not decreased through the latest-Cretaceous Lancian formation. Archibald, in his 1996 book, argued that Russell's analysis was faulty because it was conducted at the coarser genus level, not the species level, and because it assumed huge variations in sampling levels that had not been proved to be real.[323] Both Archibald and Clemens, as discussed more fully in Chapter 3, made extensive studies of the Hell Creek formation in Montana and argued both that dinosaurs had declined in diversity during the last few million years before the Cretaceous-Tertiary boundary, and that dinosaurs appear to have gone extinct below the level of the iridium anomaly. Both Clemens and Archibald argued, individually and jointly, that the best interpretation of the Hell Creek fossil succession was a gradual, not a catastrophic, extinction. For example, in a 1982 paper published in *American Scientist*, Archibald and Clemens concluded:

> 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.[324]

Another diversity study appeared in the May 2, 1986 issue of *Science*, and was written by vertebrate paleontologists Robert E. Sloan, J. Keith Rigby, Jr., Leigh M. Van Valen, and Diane L. Gabriel.[325] Sloan et al compared the number of dinosaur genera

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321 Russell, *A Census of Dinosaur Specimens.*
322 Dale A. Russell, "Reptilian diversity and the Cretaceous-Tertiary transition in North America," in W. G. E. Caldwell, ed., *The Cretaceous System in the Western Interior of North America* (The Geological Association of Canada Special Paper No. 13, Montreal: Les Presses Elite, 1975).
323 Archibald, *Dinosaur Extinction and the End of an Era*, 35-36.
324 Archibald and William Clemens, "Late Cretaceous extinctions," 384.
325 Sloan et al, "Gradual dinosaur extinction and simultaneous ungulate radiation in the Hell Creek Formation," 629-633.

present at several intervals through the last 10 million years of the Cretaceous, and concluded that dinosaur diversity declined from 30 genera (Judithian fauna) to 22 genera (Edmontonian fauna) to 19 genera (Lancian fauna).[326] Sloan et al noted that a new fauna of mammalian genera seems to have appeared just at the time of minimal dinosaurian diversity. The authors also discovered remains of dinosaurs and mammals in a Paleocene channel above the coal horizon commonly used to designate the K-T boundary in this area, leading them to suggest that dinosaurs survived into the beginning of the Tertiary period, after the bolide impact.

Subsequent authors challenged Sloan et al on these latter two points: dinosaur decline contemporaneous with mammalian diversification, and survival of dinosaurs into the Paleocene. In his 1986 paper "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," which was discussed more fully in Chapter 3, William A. Clemens wrote that "it is clear that a temporal lag existed between extinctions of Cretaceous lineages and appearances of new groups of mammals."[327] Likewise, in his 1996 book *Dinosaur Extinction and the End of an Era*, J. David Archibald stated that while the channels at Hell Creek are probably Paleocene in age, any dinosaur fossils within them have almost certainly been reworked from older Cretaceous deposits.[328]

Finally, in the late 1980s, Sheehan and Fastovsky conducted an ambitious survey of the vertebrate remains in the Hell Creek area. In a *Science* editorial published in January 1991, Richard A. Kerr reported that Sheehan and his group had found no evidence that dinosaur species had been in decline prior to the K-T boundary.[329] In their paper reporting the results of their survey, however, Sheehan and Fastovsky do not discuss the tempo of extinctions at or below the K-T boundary, but do state that in Hell Creek at least, only 12% of land-dwelling terrestrial vertebrates survived the K-T event, whereas the survival rate among freshwater vertebrates was 90%. As discussed in

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[326] *Ibid.*, 629.
[327] William Clemens, "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," 74.
[328] Archibald, *Dinosaur Extinction and the End of an Era,* 37.
[329] Richard A. Kerr, "Dinosaurs and friends snuffed out?" *Science* vol. 251, no. 4990 (January 11, 1991), 160.

Chapter 3, Sheehan and Fastovsky argued that the impact model accorded well with these observed survival rates.[330]

The different survival rates of various species across the K-T boundary was another major basis on which vertebrate paleontologists challenged the Alvarez hypothesis. Paleontologists were not content with the vague statements of many impact supporters suggesting that the various corollaries of impact – including a worldwide dust cloud, global forest fires, acid rain, impact winter, and global warming – ought to be sufficient to explain the extinction patterns, and their even vaguer assertions that "the expected biological consequences [of impact] match quite closely the extinctions observed in the fossil record."[331]

Works subsequent to the 1980 Alvarez paper, by the Alvarez team themselves and by other impact supporters, continued to oversimplify, misconstrue, or outright ignore the selectivity of extinctions visible in the fossil record. For example, in his 1997 book *T. rex and the Crater of Doom*, Walter Alvarez devoted just over two of the book's 185 pages to the biological consequences of impact – this despite the fact that the extinction's most prominent victim graces the title of the book.[332] Alvarez's discussion of the mass extinction was brief and unsatisfying; he stated several times that 'no one knows why some animals went extinct and others survived'[333], and offered only the vague suggestion that smaller creatures would be less vulnerable to extinction than larger creatures, because there are more of the former than of the latter.[334]

One of the biggest problems in attempting to match the impact scenario with the observed extinction record was the predicted acid rain. Most impactors agreed that one of the main consequences of a bolide impact would be extremely acidic rainfall, and acknowledged that surface marine and freshwater organisms would be most greatly affected by this acid rain. None of them, however, could offer a convincing explanation of why of all species, freshwater organisms suffered the fewest extinctions. For example, in their Snowbird I paper "Chemical consequences of major impacts on Earth," John S.

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[330] See Chapter 3.
[331] Luis Alvarez et al, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," 1095.
[332] Walter Alvarez, *T. rex and the Crater of Doom*, 15, 130.
[333] Ibid., 15.
[334] *Ibid.*, 15, 130.

Lewis et al argued that intense acid rain could explain the selectivity of marine plankton extinctions, since it would dissolve the shells of calcareous plankton, rendering them extinct. Lewis et al stated that their predicted concentrations of acid rain would be lethal to exposed plants and animals, but also noted that freshwater reptile and amphibian genera did not suffer severe extinctions at the K-T (in fact, they increased in number at this time). Nowhere in their paper do they explain why the acid rain did not have an adverse effect on freshwater organisms. Perhaps we are to assume that acid rain only fell on the oceans.

The apparent contradiction between the effects of acid rain and the lack of freshwater extinctions might have been explained away by invoking buffering soils that diluted the acid rain, or limestone caves that might have acted as refuges for terrestrial and freshwater organisms.[335] Archibald, however, has pointed out that there were no such buffering soils or limestone caves in latest Cretaceous North America, so there appeared to be serious problems with the acid rain scenario.[336]

An account that did take into consideration the differential extinctions in the vertebrate fossil record was Archibald's book *Dinosaur Extinction and the End of an Era*. In it, Archibald presented a well thought out and convincing argument for sea level regression as the cause of the terrestrial extinctions. Archibald also acknowledged that other potentially devastating events had occurred at or near the end of the Cretaceous period. While paleontologists were by and large convinced that a K-T impact had occurred, many vertebrate paleontologists, including Archibald, recognized that the end of the Cretaceous was a time of massive volcanism, dramatic sea level change, and climate change as well. As discussed briefly in Chapter 2, the Deccan Traps of India erupted for between 500,000 years to four million years right around 65 million years ago, creating the second-largest volcanic outpouring yet known and possibly darkening skies with volcanic ash, saturating surface waters with acid rain, and poisoning grazers of terrestrial vegetation with toxic levels of selenium. The early Cretaceous was also a time of maximum transgression, when the lowest areas of all continents were covered by

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[335] Archibald, "I. Extinction, Cretaceous," 255. While Archibald stated that some scientists have made this claim, he did not provide examples or citations.
[336] *Ibid.*, 255.

shallow epicontinental seas. These epicontinental seas provided a huge living area for shallow marine organisms, and also created vast areas of coastal plains for terrestrial organisms to inhabit. When sea level dropped during the last 10 million years of the Cretaceous period, these epicontinental seas withdrew, greatly reducing the former extent of shallow marine and coastal habitats, and reconnecting previously isolated terrestrial areas.

Many vertebrate paleontologists, notably Archibald, felt that the evidence linking extinctions to these other causes was more convincing than that supporting the impact hypothesis. As dinosaur paleontologist Peter Dodson of the University of Pennsylvania put it, the impact advocates "may have a smoking gun, but some victims died of stab wounds."[337]

In summary, vertebrate paleontologists did not accept the statements made by outsiders *telling* them that the extinction patterns matched the impact scenario; instead, vertebrate paleontologists called for an actual *examination* of the fossil record to document what the extinction patterns really were. The determination of which extinction hypotheses best explained these patterns could only be made after this examination, not before; or as William Clemens stated: "an understanding of the nature of the causal factors of extinctions during the Cretaceous-Tertiary transition will come from a summation of answers concerning the probable causes of extinction of individual lineages, *not from the imposition of a hypothesis that dictates the cause of their extinction*."[338] Archibald echoed this sentiment in his 1996 book:

> As a vertebrate paleontologist I am painfully aware of instances in which scientists who are not vertebrate paleontologists fail to fully deal with or even misconstrue what the vertebrate fossils across the K/T boundary actually say – and, just as important, on what issues the fossils are silent. Theories of extinction must ultimately stand, fall, or at least be revised based upon how well they explain patterns of biotic turnover. Simple counts of the percentages of extinction or survival in various taxa do not constitute a test of a theory's veracity.[339]

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[337] Peter Dodson, qtd. in Richard A. Kerr, "Did an asteroid leave its mark in Montana bones?" *Science* vol. 256, no. 5062 (June 5, 1992), 1395.
[338] William Clemens, "Evolution of the terrestrial vertebrate fauna during the Cretaceous-Tertiary transition," 78 (Emphasis added).
[339] Archibald, *Dinosaur Extinction and the End of an Era,* 171.

In the above quotation, Archibald referred to 'issues on which the fossils are silent.' Despite the fact that several vertebrate paleontologists, including Archibald himself, argued that the terrestrial vertebrate fossil record supported the gradualist extinction model(s), Archibald and others also argued that this same evidence was ultimately 'silent' on the question of extinction cause. The ambiguity of the vertebrate fossil record, and the contradictory ways in which this ambiguity was interpreted and appropriated by scientists in the impact debate, are discussed below.

In contrast to the vertebrate fossil record, the invertebrate fossil record, which basically corresponds to the marine fossil record, is of much better quality and quantity. Invertebrate organisms, which include a majority of microscopic creatures, are vastly more numerous in the fossil record than vertebrates, by virtue of their greater abundance in nature, their small size, and their marine environment, in which preservation in the fossil record is much more likely.[340]

There are dozens of excellent marine sections that span the K-T boundary and provide enough resolution to show the patterns of extinction among marine invertebrates; and while some of these marine invertebrates show gradual and/or pre-boundary extinction (such as the inoceramid and rudist bivalves, for example), a large number of marine invertebrate species show an abrupt extinction right at the K-T boundary.[341] Invertebrate paleontologists, then, by examining the evidence of their own discipline, were much more favorably inclined towards the impact/mass extinction hypothesis than were vertebrate paleontologists, whose evidence was not so clear-cut.[342]

Many historians, sociologists, and philosophers of science, if not always scientists themselves, have argued that not only scientific theories, but scientific 'facts' as well, are socially constructed in some sense. The old understanding of the scientific method, in which it was thought that scientists first make straightforward and so-called transparent observations of the 'real' world, and then devise theories to explain them, has had to give way to the realization that all 'facts', even the initial observations of the 'real' world, are

[340] Glen, "A manifold current upheaval in science," 197.
[341] MacLeod, "K/T redux," 312.
[342] Glen, "A manifold current upheaval in science," 197. Glen also stated that micropaleontologists are employed in the oil industry, which does not provide them with much opportunity to consider extinction

always already to some degree theory-laden. The history of science is rife with examples where scientists have seen only what they could have expected to see, or chosen the model or hypothesis which best fit their preexisting notions solely for that reason. As invertebrate paleontologists Derek Ager puts it: "Perhaps I am becoming a cynic in my old age, but I cannot help thinking that people find things that they expect to find."[343]

The concept of underdetermination describes the situation in which a particular fact or group of facts does not provide scientists with the means to choose among competing theories: these facts do not (in and of themselves) *determine* which theory is correct (or more correct). Some sociologists of science, including David Bloor and Michael Mulkay, have suggested that all knowledge, including scientific knowledge, is socially constructed, and that underdetermination is the usual situation in constructing this scientific knowledge.[344] Underdetermination suggests that when presented with a group of facts, there are a number of theories that could explain the facts equally well. Because the facts themselves do not provide a means of choosing among these theories, the choice of one theory over the others must be based on something non-factual, non-scientific: in other words, this decision must be a social one.[345]

Philosopher of science James Robert Brown does not subscribe to the theory of underdetermination, and in 1989 provided what he called its "ultimate refutation"[346]. Brown noted that in the history of science, there have been few cases of true underdetermination, and many more cases in which scientists only had to choose between a small number of competing theories. And, as Brown wrote, "in almost every case the

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from a paleobiological perspective, and which typically regards extinction levels and other geological horizons as "knife-sharp boundaries."

343 Ager, *The New Catastrophism*, 190.

344 David Bloor, *Knowledge and Social Imagery*, 2nd ed. (Chicago: University of Chicago Press, 1991).

345 Michael Mulkay, *Science and the Sociology of Knowledge* (London: George Allen & Unwin, Ltd, 1979), 61-62.

346 James Robert Brown, *The Rational and the Social* (London and New York: Routledge, 1989), 54. Brown noted that if there are infinitely many theories for a scientist to choose from, then there are infinitely many theories which will serve his or her interests equally well. So even if we admit that a scientist chooses a theory for social, not scientific, reasons, we are still left with the problem of why his or her interests dictated the choice of that particular theory over an infinite number of other theories which also would have served those social interests. The only way out of this infinite regression of theories and interests, according to Brown, is to admit that scientists are not really choosing from an infinite number of competing theories.

data did single out one theory as being better than its available rivals."[347] In those few instances where true underdetermination has occurred, Brown claimed, it also has not helped the constructivist argument, because in those cases scientists have recognized that their theory choice is a matter of convention. When scientists recognize that they are choosing one theory over its equally plausible rivals not because it is true but by convention (perhaps because it is easier to use), this recognition refutes the anti-rationalist model. The theory choice serves no social interest beyond the stated one: that it is easier to use.

What Brown described above is the response of scientists "when faced with an example of what *they believe* is real underdetermination."[348] But what happens when scientists encounter a situation in which evidence is difficult to interpret, the same facts may be used to support or to refute the same theory, scientists of different disciplines and/or subscribing to different theories ask different questions and employ different standards of evidence, and there are no clear-cut answers... but all parties remain convinced that the 'truth' will eventually be revealed? This is the situation vertebrate paleontologists have faced in trying to interpret the evidence in the terrestrial/vertebrate fossil record spanning the Cretaceous-Tertiary boundary.

The evidence of the vertebrate fossil record is unique in the impact/extinction debate in terms of its ambiguity. As paleontologist Karl Flessa points out, the current body of knowledge regarding the K-T mass extinctions, in particular the terrestrial fossil evidence, does not point to a unique extinction cause, and can in fact be used to support both gradual endogenous and catastrophic extraterrestrial models.[349] Flessa's point is wonderfully illustrated by the various interpretations of the Hell Creek Formation in Montana.[350] The Hell Creek stratigraphy is complex and not easily understood; it was deposited as a meandering river system and therefore consists of intermittent fluvial deposits later cut into and refilled by channels of younger sediment. The paleontologists and geologists studying Hell Creek in detail – some for twenty years or more – cannot

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[347] *Ibid.*, 51.
[348] *Ibid.*, 52 (Emphasis added).
[349] Flessa, "The 'facts' of mass extinction", 1. Flessa also stated the facts equally support a third model, that of stepwise extinction by a series of impacts. This third model can be seen as a blending of or compromise between the other two models and, for lack of space, will not be discussed here.

even agree on the relative ages of the various deposits or the position of the K-T boundary at Hell Creek, and there is even more disagreement over the nature of the vertebrate fossil record in this area.

Most vertebrate paleontologists, including those who work on the Hell Creek formation, agree that Hell Creek does not provide a good enough picture to determine what was happening with dinosaurs and other terrestrial vertebrates at the close of the Cretaceous in North America, and certainly should not be taken as indicative of what was happening all over the world at this time. For example, William A. Clemens, who has studied the Hell Creek sections for decades, said in an interview with William Glen:

> [Vertebrate paleontologist] Lowell [Dingus] demonstrated that the deposition of sediments entombing fossils in the Hell Creek and Tullock Formations probably was so intermittent that we could not hope to distinguish between patterns of gradual or abrupt change in composition of the biota just before or after the extinction event. ... I think Bob Dott [1983] accurately summed up the limitations of this type of study when he noted that stratigraphic sections, and the fossil records they preserve, are akin to a poor grade of Swiss cheese – more air than reality.[351]

Clemens's former student J. David Archibald has expressed similar reservations about Hell Creek:

> Until we vertebrate paleontologists are able to assemble a record of dinosaur extinction that is at least passingly global, nobody is justified to argue (or worse, to assume) anything about the temporal qualities of the dinosaur extinction. You cannot say it was instantaneous. You cannot say it was gradual. All you can say is that something of global proportions happened to the terrestrial biota during the K/T transition, and we are literally only beginning to scratch the surface.[352]

An important point to be gleaned from the above quotation is that Archibald did not believe the evidence of the vertebrate fossil record to be an example of underdetermination. Instead, Archibald expressed confidence that the truth will be revealed when vertebrate paleontologists have 'assembled a global record of dinosaur extinction.'

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[350] See Chapter 3.
[351] William Clemens, "On the mass-extinction debates: an interview with William A. Clemens," 243.
[352] Archibald, *Dinosaur Extinction and the End of an Era*, 18.

Dale Russell agreed with Clemens and Archibald's assessment of the dinosaur fossil record:

> You cannot study why the dinosaurs died by studying dinosaurs. It's just crazy. It's insane. ... There are three hundred [and] eleven skeletal fragments of dinosaurs, worldwide, for the last nine million years of Cretaceous time... I have zero patience for guys who are going to prove that dinosaurs are dying out slowly by counting dinosaur skeletons.[353]

However, despite the universal agreement that the vertebrate fossil record, particularly the dinosaur fossil record, is too poor to permit any determination of gradual or catastrophic extinction to be made, this agreement has not in fact stopped any of the players involved from making such determinations.[354] Notwithstanding his own pronouncement that it's 'just crazy' to try to understand dinosaur extinction by 'counting dinosaur skeletons', Russell did just that: he compiled a database of North American dinosaur families from the last several million years of the Cretaceous and used it to argue that dinosaurs show no decrease in diversity prior to the K-T boundary. Clemens, for his part, despite calling the vertebrate record at Hell Creek 'more air than reality', used this record to argue that dinosaurs became extinct well below the K-T boundary. The examples of Russell's and Clemens's use of the ambiguous vertebrate fossil record to argue for opposite extinction models is an excellent demonstration of theory operating on fact.[355]

As we have seen, the evidence of the vertebrate fossil record, in particular the evidence associated with the extinction of the dinosaurs, could be accommodated by many theories, encompassing both gradual terrestrial and catastrophic extraterrestrial models. In the face of this ambiguity, the theoretical and social predispositions discussed in this chapter provided the rationale for vertebrate paleontologists to choose the gradualist model(s) over the impact model. In contrast, impact supporters did not share these same theoretical and social commitments and thus interpreted the ambiguous

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[353] Dale A. Russell, qtd. in Psihoyos and Knoebber, *Hunting Dinosaurs*, 258.
[354] As discussed earlier in this chapter.
[355] It is also possible that, in the face of such an overwhelming consensus among impact supporters that the mass extinction was caused by impact, some gradualist paleontologists have overinterpreted their data simply in an effort to keep the debate open.

vertebrate fossil evidence as support for the impact theory. In the case of both groups, it was their underlying social and theoretical commitments, and not the scientific evidence itself, that determined the preferred extinction mechanism.

Conclusion

When the Alvarez team – consisting of a physicist, a geologist, and two nuclear chemists – proposed their impact hypothesis to account for the Cretaceous-Tertiary mass extinction, hundreds of scientists from a multitude of disciplines quickly joined the debate. Many of these scientists followed the Alvarez team in searching only for evidence of the impact itself, and not questioning the link between impact and extinction. The experts on mass extinction – the paleontologists – were divided. Most invertebrate paleontologists, who found evidence for catastrophic extinction among the groups they studied, supported the impact hypothesis.[356] Most vertebrate paleontologists, however, did not see evidence for abrupt, synchronous extinctions among vertebrate groups at the end of the Cretaceous period. Although most vertebrate paleontologists were convinced by the evidence amassed by impact supporters that an impact had occurred, they did not believe that this impact was the (sole) cause of the K-T mass extinction.

Among vertebrate paleontologists, only Dale Russell immediately took the impactors' side, because only Russell had a prior commitment to a catastrophic extinction model. Russell's work on dinosaur intelligence in the 1960s and 70s convinced him that dinosaurs had been a group of evolutionarily successful and potentially intelligent creatures who had not become extinct through normal selective pressures or because of any kind of unfitness, and who must therefore have been exterminated through some accident or catastrophe. Likewise, his examination of the diversity of latest Cretaceous North American dinosaur species led Russell to believe, contrary to prevailing paleontological opinion, that dinosaurs had not experienced a gradual decline, but had died out rapidly. These beliefs – that dinosaurs were exterminated rapidly, and while they were otherwise prospering – predisposed Russell to favor a catastrophic, extraterrestrial explanation for the dinosaurs' extinction. Russell published several

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[356] Some invertebrate paleontologists, particularly those who saw a more complex extinction pattern in the groups they studied, did not support the Alvarez impact hypothesis. See for example:
Hans Jorgen Hansen, "Diachronous extinctions at the K/T boundary; a scenario," in Sharpton and Ward, eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality,* 417-423.

papers arguing for the supernova extinction model in the 1970s, but when the Alvarez team presented their evidence, which disproved the supernova hypothesis and suggested a bolide impact instead, Russell immediately embraced the new theory. Both the supernova and impact hypotheses invoked catastrophic, extraterrestrial extinction mechanisms whose victims need not be unfit according to normal evolutionary pressures, and thus both hypotheses complemented Russell's unique views about dinosaurs.

With the exception of Dale Russell, vertebrate paleontologists were almost universal in their rejection of the Alvarez hypothesis, but this rejection remained primarily silent. Vertebrate paleontologists did not initially respond to the Alvarez hypothesis because it did not seem necessary to take it seriously.[357] With no paleontologists on the Alvarez team, and with the invocation of such an unusual extinction mechanism – an extraterrestrial impact – the Alvarez hypothesis was not immediately distinguishable from the multitude of silly solutions proposed by any number of armchair speculators over the past hundred and fifty years, which vertebrate paleontologists had learned to simply ignore.[358] Eventually, as evidence for a bolide impact mounted, vertebrate paleontologists were forced to take the impact theory seriously – but here again it was possible to dismiss it as an extinction mechanism, as the evidence of the vertebrate fossil record did not show the kind of abrupt, synchronous extinctions predicted by the impact model.

However, as scientists of other disciplines assumed, ignored, or misinterpreted the evidence of the vertebrate fossil record in their support of the Alvarez hypothesis, a few vertebrate paleontologists did speak out, to try to correct the misrepresentations and oversights abounding on the subject of the dinosaurs in particular, and the mass extinction in general. The most vocal opponents to impact theory who arose among vertebrate paleontologists were those who had spent the most time studying the actual record of dinosaur extinction, and were therefore most acutely aware of the inaccuracy of the theories and evidence being brought forth by the impact supporters. These outspoken

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Norman MacLeod and Gerta Keller, "Comparative biogeographic analysis of planktic foraminiferal survivorship across the Cretaceous-Tertiary (K/T) boundary," *Paleobiology* vol. 20, no. 2 (Spring 1994): 143-177.
[357] Powell, *Night Comes to the Cretaceous*, 126-127.

paleontologists were those most familiar with the Hell Creek area of Montana: William A. Clemens and his former student J. David Archibald.

Thus, only a handful of vertebrate paleontologists participated in the impact debate, and in many cases their comments, cautions and criticisms, as well as the evidence they presented, were misrepresented, dismissed, or outright ignored. Although the reluctance of vertebrate paleontologists to embrace the impact theory as the extinction cause was noted throughout the debate, very few attempts have been made to explore the reasons behind this reluctance, and the reasons why the arguments and evidence presented by the few vertebrate paleontologists who did speak out were not heard.

As discussed in Chapter 4, vertebrate paleontologists rejected the Alvarez hypothesis because it was an invasion of their scientific territory by disciplinary outsiders from a higher level on the perceived hierarchy of sciences, who presented themselves as superior to, more scientific than, and more knowledgeable than vertebrate paleontologists, but who at the same time revealed their ignorance of biological complexity and their devotion – ludicrous, by paleontologists' standards – to the principle of reductionism. At the same time, as we have seen, the evidence of the terrestrial/vertebrate fossil record was unique in the impact/extinction debate in presenting a much more complex picture of extinction than could be accounted for by bolide impact alone. Only Dale Russell initially believed that the dinosaurs had died out abruptly; most other studies of dinosaur diversity showed a pronounced decline towards the end of the Cretaceous period. The Hell Creek section in Montana, which displayed the best-preserved and most-studied vertebrate fossil record across the K-T boundary, also showed a clear gap between the last known dinosaur fossil and the iridium horizon marking the bolide impact. Although the significance of this gap and the other evidence of the vertebrate fossil record were – and continue to be – hotly contested, it was certain that the vertebrate fossil record did not provide unequivocal support of the impact hypothesis.

Unlike the situation in invertebrate paleontology, the package of 'facts' particular to vertebrate paleontology was so ambiguous that it could be used to support both gradual

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[358] Benton, "Scientific methodologies in collision," 381-385. See the Introduction for a discussion of Benton's three phases of dinosaur extinction study.

endogenous and catastrophic extraterrestrial extinction causes – or, indeed, any number of intermediate causes as well. In the face of this ambiguity, then, and combined with the above-mentioned overwhelmingly negative social factors, it is unsurprising that the majority of vertebrate paleontologists ignored the Alvarez hypothesis and sided with their prior theoretical and conceptual commitments. Most vertebrate paleontologists continued to believe in the more traditional gradual endogenous paradigm of mass extinction, which carried none of the social stigma of the Alvarez theory, upheld traditional beliefs in gradualism, terrestrial causation, and biological complexity, and above all, relied on the evidence of the vertebrate fossil record as its proof and final arbiter.

These conclusions of the vertebrate paleontology community, and their own beliefs about the cause(s) of the K-T mass extinction, have not been heard, and to most other participants in and commentators on the impact debate, the question of what killed the dinosaurs was settled in favour of the impactors long ago. Consider the following quotation, taken from a review of planetary geologist Charles Frankel's pro-impact book *The End of the Dinosaurs: Chicxulub Crater and Mass Extinctions*, written by environmental scientist and science writer Antony Milne:

> The prevailing orthodoxy [of gradual endogenous extinction mechanisms, particularly volcanism] was finally overturned because of what was known about earth processes and the discovery of minerals that were clearly and irrefutably of extraterrestrial origin. It was not just the presence of the renowned iridium at the K-T geological boundary, but also the finding of osmium and palladium – not at all the kinds of metals a volcano would produce in such vast amounts. ... What is commendable about Frankel's illustrated book is the quiet, step-by-step manner in which he shows how the catastrophic explanation scientifically and empirically defeated the 'gradualist' one. At a symposium in 1994 not a single geologist contested the impact thesis nor disputed the date or size or location of the impact site.[359]

Two conclusions can be drawn from Milne's review (and from Frankel's book): one, the extinction debate is over, the impact hypothesis having won out over its gradualist opponent(s); and two, this victory was accomplished by the discovery of extraterrestrial minerals (such as iridium, osmium, and palladium) which could only have come from a bolide impact and not a volcanic eruption. What Frankel and Milne, and countless other supporters of the impact theory, fail to grasp, is that all of this evidence – the extraterrestrial quantities of iridium, osmium, and palladium, the date, size, and location of the impact site – proves only that an impact occurred, not that it had any connection – other than a close proximity in time – to the K-T mass extinction. Neither Frankel nor Milne even mentions the only evidence that exists for directly examining the mass extinctions at the end of the Cretaceous period: the fossils entombed in those Cretaceous rocks.

Milne's review can be contrasted with other reviews, written by vertebrate paleontologists. The first is "Catastrophes, expectations, and the evidence," a review of the proceedings of the first Snowbird conference, by Leigh M. Van Valen.[360] Van Valen summarized the various papers presented in the volume, most dealing with the hypothesized effects of a bolide impact, and a few describing the patterns of extinction among vertebrate and invertebrate groups. Van Valen concluded with two juxtaposed lists, which he described as "evidence for and against a K-Pg impact."[361] In reality, Van Valen's lists combined evidence dealing with both parts of the impact hypothesis; that is, evidence for an impact proper, and evidence of the connection between impact and extinction. Most of the 'evidence for impact' is just that: geochemical and physical evidence suggesting that there was an impact at the end of the Cretaceous period. In contrast, most of what Van Valen listed as 'evidence against impact' is not what this label literally states, but is in fact evidence that extinctions were caused by mechanisms other than impact. Van Valen was aware of the incommensurability of these two lists of evidence, and concluded that "[S]elective use of available evidence can be very convincing in either direction. The best evidence for each side does not impinge on that for the other, and neither side has a satisfactory explanation for the opposing evidence."[362] As we saw in Chapter 4, this ambiguity of the fossil evidence allowed debate participants to use it to support whatever extinction model they had already selected for reasons other than the scientific evidence.

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[359] Milne, "Book review," 678-679.
[360] Leigh M. Van Valen, "Catastrophes, expectations, and the evidence," *Paleobiology* vol. 10, no. 1 (Winter 1984): 121-137.
[361] *Ibid.*, 130.
[362] *Ibid.*, 131.

David Jablonski, a geologist/biologist, in his article "Keeping time with mass extinctions," reviewed a workshop held at the Lawrence Berkeley Laboratory on March 3-4, 1984.[363] This workshop was convened primarily to discuss the periodic extinction hypothesis, which had just been proposed, but the question of impact-driven extinction at the K-T was still very much open. Jablonski wrote:

> The hypothesis that geochemical and other geological anomalies at the end of the Cretaceous are the signature of an extraterrestrial impact appears to have weathered an intensive round of testing. ... In far greater disarray is the question of most concern to paleobiologists: What are the biological effects of such impacts if or when they occur?[364]

Jablonski noted that the postulated effects of impacts were still being worked out, but cautioned that the majority of impact models "appear to be too severe and too rapid to account for the complex patterns of extinction and survival documented at the end of the Cretaceous or at other supposedly impact-generated extinctions." Jablonski concluded that "Paleontology will still be the final arbiter regarding the biological effects of extraterrestrial impacts or any other forcing mechanism."[365]

Another review was written by vertebrate paleontologist Anne Weil, on the subject of William Glen's volume *The Mass-Extinction Debates: How Science Works in a Crisis*.[366] Weil noted that

> The book... suffers from biased attempts to explain why many vertebrate paleontologists are so recalcitrant as to continue to view the impact hypothesis with skepticism. The most often invoked explanation is the specter of Lyellian uniformitarianism as justification for an institutional repression of noncatastrophic ideas.[367]

Weil also discussed Glen's repeated mention of Digby McLaren's 1970 presidential address, in which he suggested that a bolide impact might have caused the Frasnian-

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[363] David Jablonski, "Keeping time with mass extinctions." *Paleobiology* vol. 10, no. 2 (Spring 1984): 139-145.
[364] *Ibid.*, 143.
[365] *Ibid.*, 144.
[366] Anne Weil, Book Review (*The Mass-Extinction Debates: How Science Works in a Crisis*. William Glen, ed., Stanford: Stanford University Press, 1994) *Journal of Vertebrate Paleontology* vol. 15, no. 1 (March 1995): 208-209.
[367] *Ibid.*, 209.

Fammenian mass extinction. As discussed earlier in this thesis, McLaren's theory was largely ignored by the scientists of the day, which Glen (according to Weil) "interprets as symptomatic of the inability of paleontologists to think about catastrophic, exogenous causes of mass extinction." Weil continued: "It is interesting to note that both Clemens and Gould, in their interviews [later in Glen's book], attribute the lack of attention to lack of evidence" instead. Weil's point, therefore, was that vertebrate paleontologists resisted the impact hypothesis, not out of a knee-jerk adherence to outdated uniformitarian ideals as Glen implies, but rather because of a 'lack of evidence' supporting the impact theory – a perfectly reasonable motive for doubting a hypothesis.

Finally, in her conclusion, Weil suggested that the impact debate has not been settled, and that there is more to learn not only within the framework of the debate itself, but also by studying the debate from outside:

> As Raup notes [Weil wrote], few paleontologists are now inclined to deny the historical fact of a bolide impact at the boundary. Argument has shifted to a discussion of whether or how such an impact could have affected the observed pattern of extinction and survival. ... The subject of scientific process, particularly as regards paradigm shifts, deserves attention. I hope that further attempts are made in this direction. Also, considering the high level of public awareness of and interest in the K/T boundary, and the degree to which such interest influences the academic debate, a treatment of this type aimed at a popular audience is badly needed. 'What killed the dinosaurs' may be the only paleontological question that a non-scientist is aware of – and therefore the only window to explanation of what a diverse, contentious, and significant field paleontology really is.[368]

Although the present work, as a master's thesis, is not precisely aimed at a popular audience, I hope that I have provided a comprehensible analysis of the role of vertebrate paleontologists in the impact/mass extinction debate. If nothing else, I hope I have shown that, with respect to the popular question 'What killed the dinosaurs?' the jury – which is and should be composed of the vertebrate paleontologists who study the remains of the dinosaurs – has not yet returned a verdict.

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[368] *Ibid.*

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Appendix A:
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Appendix B:
Analysis of *Science* Articles

Appendix B

Vertebrate Paleontologists	Vertebrate Paleontologists
Archibald, J. David	McKenna, Malcolm C.
Benton, Michael J.	Olsen, Paul E.
Berghaus, Claudia B.	Padian, Kevin
Brinkman, Donald B.	Penny, David
Bryant, Laurie J.	Prothero, Donald R.
Clemens, William A.	Rich, Patricia Vickers
Dawson, Mary R.	Rich, Thomas H.
Fastovsky, David E.	Rigby, Jr., J. Keith
Flynn, John J.	Russell, Dale A.
Gabriel, Diane L.	Schopf, Thomas J. M.
Hoganson, John W.	Sloan, Robert E.
Hutchison, J. Howard	Sues, Hans-Dieter
MacFadden, Bruce J.	Van Valen, Leigh M.
Marshall, Charles R.	West, Robert M.

Invert./Other Paleontologists	Invert./Other Paleontologists
Ager, Thomas A.	Keigwin, Jr., Lloyd D.
Anders, Mark H.	Keller, Gerta
Aubry, Marie-Pierre	Kitchell, Jennifer A.
Bambach, Richard K.	Knoll, Andrew H.
Berggren, William A.	MacLeod, Norman
Bourgeois, Joanne	McEwen Mason, Jennifer R. C.
Brouwers, Elisabeth M.	Maurasse, Florentin J-M. R.
Carter, Elizabeth S.	McMenamin, Mark A. S.
Casier, Jean-Georges	McRoberts, Christopher A.
Chamberlain, C. Page	Newton, Cathryn R.
Choi, Duck Keun	Nichols, Douglas J.
Clark, David L.	Oberhaensli, Hedy
Cobban, William A.	Palmer, Allison R.
Collen, John D.	Perch-Nielsen, Katharina
Cvancara, Alan M.	Percival, Stephen F.
D'Hondt, Steven	Poore, Richard Z.
Ekdale, Allan A.	Raine, J. Ian
Erickson, J. Mark	Raup, David M.
Erwin, Douglas H.	Retallack, Greg
Gartner, Stefan	Sepkoski, Jr., J. John
Haggart, James W.	Sheehan, Peter M.
Hallam, Anthony	Sliter, William V.
Hansen, Thor A.	Spicer, Robert A.
Hickey, Leo J.	Surlyk, Finn
Hoffman, Antoni	Vermeij, Geerat J.
Holland, Jr., F. D.	Wagstaff, Barbara E.
Hollis, Christopher J.	Wang, W.
Huber, Brian T.	Wang, Y.
Jablonski, David	Ward, Peter D.
Jarzen, David MacArthur	Wolfe, Jack A.
Jin, Y. G.	Wright, Ramil C.
Johansen, Marianne Bagge	Yang, Xing-Hua
Kauffman, Erle G.	

(Co-) Author	Institution	Scientific Area	# Articles	# Letters etc.	# Editorials
Abelson, Philip H.			1		
Ackerman, Thomas P.	NASA Ames		1		
Ager, Thomas A.		invert paleo	1		
Al'Mukhamedov, Alexander I.			1		
Alvarez, Luis W.	University of California at Berkeley (UCB), deceased	particle physicist	5	1	
Alvarez, Walter	UCB	geologist	8	1	
Anbar, A. D.			1		
Anders, Edward		chemist??	1	1	
Anders, Mark H.		invert paleo	1	1	
Andersson, P. S.			1		
Archibald, J. David	Dept. of Biology, Yale University	vert paleo		2	
Arden, J. W.			1		
Argyle, Edward				1	
Asaro, Frank	Lawrence Berkeley Laboratory (LBL), & UCB	nuclear chemist	7	1	
Aubry, Marie-Pierre		invert paleo	1		
Bada, Jeffrey L.			1		
Bambach, Richard K.		invert paleo	1	1	
Becker, Luann			2		
Becker, Timothy A.			1		
Bender, Michael L.			1		
Benton, Michael J.	Dept. of Geology, Queen's Univ. of Belfast	vert paleo	2	1	
Berggren, William A.		invert paleo	1		
Berghaus, Claudia B.	Dept. of Geology, Milwaukee Public Museum, Wisconsin	vert paleo	1	1	
Berry, William B. N.			1		
Besse, Jean		geophys??	1		
Bice, D. M.			1		
Blum, Joel D.			1		
Bohor, Bruce F.		geophys??	2	1	
Bourgeois, Joanne		invert paleo	1		
Bowring, S. A.			1		
Boynton, William V.			1		
Brinkman, Donald B.	Royal Tyrrell Museum of Palaeontology (RTMP), Drumheller, AB	vert paleo	1		
Brooks, Robert D.			1		
Brooks, Robert R.			1		
Brouwers, Elisabeth M.	United States Geological Survey (USGS), Denver	invert paleo	1	1	
Brown, Randall E.				1	
Bryant, Laurie J.	Museum of Paleontology, UCB	vert paleo		1	
Bunch, Theodore E.			1		
Burke, Kevin			1		
Byerly, Gary R.			2		
Caldeira, Ken				1	
Camargo-Zanoguera, Antonio			1		
Camilion, C.			1		
Canfield, Donald E.			1	1	
Cao, C. Q.			1		
Carman, Max F.			1		

Carter, Elizabeth S.		invert paleo	1		
Carter, L. David			1		
Casier, Jean-Georges		invert paleo	1		
Castillo, P.			1		
Cedillo-Pardo, Esteban			1		
Chamberlain, C. Page		trace fossils	1		
Cheng-Yuan, Wang			1		
Chibante, L. P. Felipe			1		
Choi, Duck Keun	Penn State Univ.	invert/palynology	1		
Cisowski, S. M.				1	
Claeys, Philippe			4		
Clark, David L.		invert paleo	1	1	
Clemens, William A.	UCB (retired)	vert paleo	1	3	
Clifton, H. Edward				1	
Cobban, William A.		invert paleo	1		
Collen, John D.		invert paleo	1		
Cooper, Alan			1		
Corliss, Bruce H.			1		
Cottrell, R. D.			1		
Courtillot, Vincent		geophysicist	1		
Crowley, Thomas J.			1		
Culler, Timothy S.			1		
Curtis, Garniss H.			1		
Cvancara, Alan M.		invert paleo		1	
Dalrymple, G. B.			1		
Davidek, K.			1		
Dawson, Mary R.	Carnegie Museum of Natural History, Pittsburgh	vert paleo	1	1	
D'Hondt, Steven	University of Rhode Island, Kingston, Rhode Island	invert paleo	1		
Dorritie, Daniel				1	
Dott, Jr., Robert H.		geologist??		1	
Douthitt, C. B.			1		
Drake, Charles L.			2	1	
Ekdale, Allan A.		trace fossils		1	
Erickson, J. Mark		invert paleo		1	
Erwin, Douglas H.		invert paleo	2		1
Evans, T.			1		
Farley, K. A.			2		
Fassett, James E.	USGS New Mexico	geologist	1		
Fastovsky, David E.	Dept. of Geosciences, University of Rhode Island, Kingston, RI	geologist/biologist?	1	1	
Feduccia, Alan			1		
Felton, E. A.			1		
Fenner, Julianne M.			1		
Flannery, Tim					1
Flynn, John J.	The Field Museum, Chicago	vert paleo		1	
Foord, E. E.			2		
Fowell, S. J.			1		
Franchi, I. A.			1		

French, Bevan M.			1	1	
Fuller, M.				1	
Gabriel, Diane L.	Dept. of Geology, Milwaukee Public Museum, Wisconsin	vert paleo	2	1	
Galbreath, Gary J.				1	
Ganapathy, R.			2		
Gartner, Stefan	Dept. of Oceanography, Texas A&M University	invert paleo		1	
Gibbons, Ann					2
Gilmore, James S.	Los Alamos National Laboratory, New Mexico		5		
Gilmour, I.			1		
Gombos, Andrew M.			1		
Goodfellow, Wayne D.			1		
Grajales-Nishimura, Jose M.			1		
Gregory, R. T.			1		
Grotzinger, John P.			1	1	
Haggart, James W.		invert paleo	1		
Haggerty, Bruce M.				1	
Hall, Stuart A.			1		
Hallam, Anthony		invert paleo	1		
Hames, W.			1		
Hansen, Thor A.		invert paleo	1		
Hartline, B. W.			1		
Hatfield, Craig Bond				1	
Haugerud, R. A.			1		
He, Q.			1		
Hess, Jennifer			1		
Heyman, Dieter			1		
Hickey, Leo J.	Yale University	paleobotanist	1	2	
Hildebrand, Alan R.			1		
Hoffman, Antoni		invert paleo		1	
Hoffman, Raymond G.			1	1	
Hoganson, John W.	Paleontology, North Dakota Geological Survey, Bismarck, ND	vert paleo		1	
Holland, Jr., F. D.		invert paleo		1	
Hollis, Christopher J.		invert paleo	1		
Holzbecher, Jiri			1		
Hsu, Kenneth J.			1		
Huber, Brian T.		invert paleo			1
Huber, H.			1		
Hunt, Andrew G.			1		
Hutchison, J. Howard	Museum of Paleontology, UCB	vert paleo		1	
Izett, G. A.			3		
Jablonski, David	Dept. of Geophysical Sciences, University of Chicago	invert paleo	4		
Janzen, Daniel H.				1	
Jarzen, David MacArthur	Florida Museum of Natural History	paleobotanist	1		
Jin, Y. G.		invert paleo	2		
Johansen, Marianne Bagge		invert paleo	1		
Karpoff, Anne Marie			1		
Kastner, M.			1		

Kauffman, Erle G.	Dept. of Geological Sciences, University of Colorado	geol/invert paleo	2		
Keigwin, Jr., Lloyd D.		invert paleo	1		
Keller, Gerta	University of Princeton	invert paleo	2	1	
Kelley, Simon			1		
Kelts, Kerry			1		
Kent, Dennis V.				1	
Kerr, Richard A.				2	45
Kieffer, Susan W.			1		
King, J.			1		
Kirda, Nikolay P.			1		
Kitchell, Jennifer A.		invert paleo	1		
Knight, Jere D.	Los Alamos National Laboratory, New Mexico		3		
Knoll, Andrew H.		invert paleo	1	1	
Koeberl, Christian			2		
Koshland,Jr., Daniel E.				1	
Krahenbuhl, Urs			1		
Kunk, M. J.			2		
Kyte, Frank T.			4	2	
LaBrecque, John			1		
Leahy, Guy D.				1	
Lee, D. Scott			1		
Lee, Julian			1		
Lee, M. R.			1		
Lewin, Roger				1	6
Lewis, Charles F.			1		
Lewis, Roy S.		chemist??	1	1	
Lindstrom, David J.			1		
Lowe, Donald R.			2		
Luck, J. M.			1		
Lugmair, G. W.			1		
Macdougall, J. D.			1		
MacFadden, Bruce J.	Florida Museum of Natural History, Univ. of Florida	vert paleo		1	
MacLeod, Norman		invert paleo		1	
Margolis, Stanley V.			3		
Marin, Luis E.			2		
Marshall, Charles R.	Dept. Earth&Space Sci/Molecular Biol Inst./Inst. for Geophys&Planetary Phys, UCLA	vert paleo	1		
Martin, M. W.			1		
Martin, Ronald E.				1	
Martinez, Rene R.			1		
Maurasse, Florentin J-M. R.		invert paleo	2		
McCauley, S.			1		
McEwen Mason, Jennifer R. C.		invert paleo	1		
McHone, J. F.			1		
McKay, Christopher P.	NASA Ames		1		
McKenna, Malcolm C.	American Museum of Natural History (AMNH), New York	vert paleo		1	
McKenzie, Judith A.			1		
McLaren, Digby J.			1		

McLean, Dewey M.				1	
McMenamin, Dianna Schulte				1	
McMenamin, Mark A. S.	Mt. Holyoke College, Massachusetts	invert paleo		1	
McRoberts, Christopher A.		invert paleo	1		
McWilliams, Michael O.			1		
Medvedev, Alexander I.			1		
Miall, A. D.	Geology Dept., University of Toronto	geologist??		1	
Michel, Helen V.	LBL, UCB	nuclear chemist	5	1	
Mittlefehldt, David W.			1		
Modreski, P. J.			2		
Moffat, Anne Simon					1
Montanari, Alessandro			5		
Montgomery, David R.			1		
Morell, Virginia					1
Morse, Carolyn L.				1	
Mukhopadhyay, S.			1		
Muller, Richard A.	UCB	astrophysicist	1	1	
Neall, Vincent E.			1		
Newton, Cathryn R.		invert paleo	1		
Nichols, Douglas J.		invert paleo	1		
Nieman, Ronald A.			1		
Norris, G.	Geology Dept., University of Toronto	geologist??		1	
North, Gerald R.			1		
Oberhansli, Hedy		invert paleo	1		
Obradovich, J. D.			1		
Officer, Charles B.			2	2	
Oliver, P. Q.			1		
Olsen, Paul E.	Lamont/Columbia University	vert paleo	2	1	
Opdyke, Neil D.	University of Florida	geologist			
Orth, Charles J.	Los Alamos Laboratory, New Mexico; deceased	geologist??	7		
Padian, Kevin	Museum of Paleontology, UCB	vert paleo		1	
Palmer, Allison R.		invert paleo	1		
Papanastassiou, D. A.			1		
Parker, Julian			1		
Parrington, J. R.			1		
Pena, Daniel			1		
Penny, David	Massey University, New Zealand	vert paleo/biol.	1		
Perch-Nielsen, Katharina		invert paleo	1		
Percival, Stephen F.		invert paleo	1		
Petersen, Nikolai			1		
Phelan Kotra, J. M.			1		
Pillinger, C. T.			1		
Pillmore, Charles L.	USGS Denver		3		
Pisciotto, Kenneth			1		
Playford, Phillip E.			1		
Pollack, James B.	NASA Ames		1		
Poore, Richard Z.		invert paleo	1		

Poreda, Robert J.			2		
Pringle, Malcolm S.			1		
Prothero, Donald R.	Occidental College, L.A.	vert paleo	1		
Quezada-Muneton, Juan Manuel			1		
Quinby-Hunt, Mary S.			1		
Quinn, James F.	University of California at Davis	env'tal studies		1	
Quintana, Leonard R.			2		
Raine, J. Ian		invert paleo	1		
Rainforth, E. C.			1		
Rampino, Michael R.		geologist??	4	3	
Raup, David M.		invert paleo	5	1	
Reeves, Roger D.			1		
Reichow, Marc K			1		
Reid, George C.				1	
Reiners, P. W.			1		
Renne, Paul R.	Instittue Of Human Origins, Berkeley		3		1
Retallack, Greg		invert paleo		1	
Reynolds, R. C.			1	1	
Rice, Alan				1	
Rich, Patricia Vickers	Dept. Earth Sci & Dept. Zool, Monash Univ. & Museum of Victoria, Victoria, Australia	vert paleo	1		
Rich, Thomas H.	Museum Of Victoria, Melbourne, Australia	vert paleo	1		
Rigby, Jr., J. Keith	University of Notre Dame	vert paleo	1	1	
Russell, Dale A.	North Carolina State Univ./N.C. State Museum of Natural Sciences	vert paleo		1	
Russell, S. S.			1		
Ryan, Douglas E.			1		
Saunders, Andrew D.			1		
Scher, H.			1		
Schilling, Govert			1		
Schilling, Jean-Guy			1		
Schopf, Thomas J. M.	Dept. of Geophysical Sciences, Univ.of Chicago & Div. of Biol.,Cal Tech; deceased	vert paleo	1		
Schreiber, Edward			1		
Schultz, Peter H.			1		
Schuraytz, Benjamin C.			1		
Sen, Gautam			1		
Sepkoski, Jr., J. John	deceased	invert paleo	2	1	
Shang, Q. H.			1		
Sharpton, Virgil L.			2		
Sheehan, Peter M.	Dept. of Geol, Milwaukee Public Museum, Milwaukee, Wisconsin	trace fossils	1	2	
Shirey, Steven B.			1		
Shoemaker, Carolyn S.			1		
Shoemaker, Eugene M.			1		
Shubin, Neil H.			1	1	
Shukolyukov, A.			1		
Sliter, William V.		invert paleo	1		
Sloan, Robert E.	University of Minnesota	vert paleo	1	1	
Smalley, Richard E.			1		
Smit, Jan		geolgist	2	1	

Smith, Roger			1		
Snee, L. W.			1		
Spicer, Robert A.		invert paleo	1	1	
Spudis, Paul D.			1		
Stothers, Richard B.			2		
Suarez-Reynoso, Gerardo			1		
Sues, Hans-Dieter	Royal Ontario Museum (ROM), Toronto	vert paleo	1		
Surlyk, Finn		invert paleo	2		
Sutter, J. F.			1		
Swisher III, Carl C.			1		
Szajna, M. J.			1		
Tarduno, J. A.			1		
Tauxe, Lisa			1		
Tipper, H. W.			1		
Toon, Owen Brian	NASA Ames Research Center	oceanic/atm sci	1		
Triplehorn, D. M.			1		
Tschudy, Robert H.	USGS Denver		3		
Tucker, Peter			1		
Turco, Richard Peter	R&D Associate, Marina del Rey, California	atm sciences	1		
Turekian, Karl K.			1		
Twitchett, Richard J.				1	
Urrutia-Fucugauchi, Jaime			1		
Vajda, Vivi			1		
Vallier, T. L.			1		
Van Valen, Leigh M.	Biology Dept., Univ. of Chicago	vert paleo	1		
Vander Kaars, S.			1		
Vermeij, Geerat J.	Dept. of Zoology, Univ. of Maryland	invert paleo		1	
Wagstaff, Barbara E.		invert paleo	1		
Walkden, Gordon			1		
Wang, Kun			1		
Wang, W.		invert paleo	2		
Wang, Y.		invert paleo	1		
Ward, Peter D.	Dept. of Geological Sciences, Univ. of Washington, Seattle	invert paleo	3		
Wasserburg, G. J.			1		
Wasson, John T.			2	1	
Weissert, Helmut			1		
Wentworth, Susan J.			1		
West, Robert M.	Carnegie Museum of Natural History, Pittsburgh	vert paleo	1	1	
White, Rosalind V.			1		
Wiberg, Patricia L.			1		
Wignall, Paul B.				1	
Wilbur, D.			1		
Wilde, Pat			1		
Wilson, Paul T.				1	
Wolbach, Wendy S.		chemist??	2	1	
Wolfe, Jack A.		invert paleo		1	

Wooden, Joseph L.			1		
Wright, Ramil C.		invert paleo	1		
Xie, Xiaogang			1		
Yang, Xing-Hua		invert paleo	1		
Yates, Ann M.			1		
Zarate, M.			1		
Zhou, Lei			1		
Zoller, W. H.			1		
Authors by Discipline	**Number of Authors of Each Discipline**				
Vertebrate Paleontologists	28				
Invert./Other Paleontologists	65				
Other Authors	242				
Total	335				
Authors by Discipline	**Percentage of Authors of Each Discipline**				
Vertebrate Paleontologists	8.36				
Invert./Other Paleontologists	19.40				
Other Authors	72.24				
Total	100.00				

Appendix C:

Email and Survey Sent to VRTPALEO Listserver Subscribers

[Email posted to VRTPALEO Listserver on November 17, 2002]

Subject: Survey on K-T Impact Debate: Thesis Research

Hi. My name is Keynyn Longman and I am a graduate student at the University of Alberta. I have a B.Sc. in Honors Paleontology, and I am currently working on an M.A. in History of Science. For my thesis, I am looking at the Cretaceous-Tertiary mass extinction controversy, with a specific focus on what role(s) have been played in the controversy by vertebrate paleontologists, and how the Alvarez impact hypothesis and subsequent debate have shaped the field of vertebrate paleontology.

As part of my thesis research, I have composed a survey which I would like to send off-list to anyone interested in responding. The survey comprises six questions, plus an optional information section, and shouldn't take too long to fill out (depending entirely on how much detail respondents want to include). Anyone who wishes to participate can choose to remain anonymous. Only if you give your express permission in the indicated space on the survey will I quote your answer directly and/or use your name. Any responses will be used only for the purpose of research for and publication in my master's thesis.

If you are interested in participating, please email me off-list at <klongman@ualberta.ca>, and I will email the survey to you. Thank you all in advance for your time and your insights.

Sincerely,

Keynyn Longman
klongman@ualberta.ca

Survey for Subscribers to the VRTPALEO Listserver

Name (you may leave this blank if you wish):______________________________

Institution (you may leave this blank if you wish):______________________________

Position or title:______________________________

Group, taxon, or taxa that you study:______________________________

By typing 'yes' in the following line, I hereby give permission for my responses below to be quoted directly, and such quotation to be attributed to me by name, only in the master's thesis to be published by Keynyn Longman in the spring of 2003:______________________________

By typing 'no' in the following line, I indicate that I DO NOT give permission for my name to be used or my responses below to be quoted directly anywhere, including in the master's thesis to be published by Keynyn Longman in the spring of 2003:______________________________

1. Did the group of vertebrates you study, or any subgroup within it, become extinct at or near the K-T boundary? If yes, was this extinction sudden or gradual, in your opinion?

2. Over what approximate time period do you think the end-K mass extinction took place? (e.g. dozens, hundreds, thousands, millions of years)

3. In your opinion, what caused the Cretaceous-Tertiary mass extinction? Please feel free to list as many or as few causal factors as you think are necessary to explain this event.

4. Many scientists from varied fields, from astrophysics to geology, and from paleontology to evolutionary biology, have participated in the mass extinction debates. In your opinion, have vertebrate paleontologists been significant players in this debate? How important are the mass extinction debates to your research, and to the field of vertebrate paleontology in general?

5. Are there any comments you would like to make about the Cretaceous-Tertiary impact debate, its history, and/or its impact on the field of vertebrate paleontology?

Thank you very much for your response.

Appendix D:

Raw Data and Analysis of VRTPALEO Listserver Survey

Subject	Level of Education	Current Country	Duration of K-T Mass Extinction	Cause of K-T Mass Ext.
1	Ph.D.	U.S.A.	100s - 1000s	terrestrial --> bolide
2	M.Sc.	U.S.A.	yrs	bolide impact
3	Ph.D.	U.S.A.	> 100,000 yrs	terrestrial --> bolide
4	Ph.D. Candidate	Canada	yrs	bolide impact
5	Other Qualifications	U.S.A.	> 100,000 yrs	terrestrial --> bolide
6	Ph.D.	France	not sure (but gradual)	not sure there is M.E.
7	Ph.D.	U.S.A.	> 100,000 yrs	not sure
8	Ph.D.	U.S.A.	yrs (and aftereffects)	bolide impact
9	Ph.D. Candidate	U.S.A.	not sure	terrestrial --> bolide
10	Ph.D.	U.S.A.	10,000s of yrs	terrestrial --> bolide
11	M.Sc.	Sweden	yrs or less	bolide impact
12	Ph.D.	United Kingdom	> 100,000 yrs	terrestrial --> bolide
13	Ph.D.	United Kingdom	>100, 000 yrs	terrestrial --> bolide
14	Ph.D.	United Kingdom	> 100,000 yrs	terrestrial --> bolide
15	Ph.D. Candidate	U.S.A.	not sure	terrestrial --> bolide
16	Ph.D. Candidate	Germany	sudden but not sure	terrestrial --> bolide
17	Ph.D.	U.S.A.	yrs	bolide impact
18	Ph.D.	U.S.A.	>100,000 yrs	terrestrial --> bolide
19	Ph.D. Candidate	U.S.A.	>100,000 yrs	terrestrial --> bolide
20	Ph.D.	U.S.A.	not sure >100,000yrs	terrestrial --> bolide
21	Ph.D.	U.S.A.	100s or less/not sure	terrestrial --> bolide
22	Ph.D.	U.S.A.	1000s	terrestrial --> bolide
23	M.Sc. Candidate	Canada	> 100,000 yrs	terrestrial --> bolide
24	Ph.D.	Canada	decline over my; then bolide - fast	terrestrial --> bolide
25	Ph.D.	U.S.A.	decline over my; then bolide - fast	terrestrial --> bolide

Subject #	Level of Education	Current Country	Duration of K-T Mass Extinction	Cause of K-T Mass Ext.
1	Ph.D.	U.S.A.	100s - 1000s	terrestrial --> bolide
2	M.Sc.	U.S.A.	yrs	bolide impact
3	Ph.D.	U.S.A.	> 100,000 yrs	terrestrial --> bolide
4	Ph.D. Candidate	Canada	yrs	bolide impact
5	Other Qualifications	U.S.A.	> 100,000 yrs	terrestrial --> bolide
6	Ph.D.	France	not sure (but gradual)	not sure there is M.E.
7	Ph.D.	U.S.A.	> 100,000 yrs	not sure
8	Ph.D.	U.S.A.	yrs (and aftereffects)	bolide impact
9	Ph.D. Candidate	U.S.A.	not sure	terrestrial --> bolide
10	Ph.D.	U.S.A.	10,000s of yrs	terrestrial --> bolide
11	M.Sc.	Sweden	yrs or less	bolide impact
12	Ph.D.	United Kingdom	> 100,000 yrs	terrestrial --> bolide
13	Ph.D.	United Kingdom	>100, 000 yrs	terrestrial --> bolide
14	Ph.D.	United Kingdom	> 100,000 yrs	terrestrial --> bolide
15	Ph.D. Candidate	U.S.A.	not sure	terrestrial --> bolide
16	Ph.D. Candidate	Germany	sudden but not sure	terrestrial --> bolide
17	Ph.D.	U.S.A.	yrs	bolide impact
18	Ph.D.	U.S.A.	>100,000 yrs	terrestrial --> bolide
19	Ph.D. Candidate	U.S.A.	>100,000 yrs	terrestrial --> bolide
20	Ph.D.	U.S.A.	not sure >100,000yrs	terrestrial --> bolide
21	Ph.D.	U.S.A.	100s or less/not sure	terrestrial --> bolide
22	Ph.D.	U.S.A.	1000s	terrestrial --> bolide
23	M.Sc. Candidate	Canada	> 100,000 yrs	terrestrial --> bolide
24	Ph.D.	Canada	decline over my; then bolide - fast	terrestrial --> bolide
25	Ph.D.	U.S.A.	decline over my; then bolide - fast	terrestrial --> bolide

Level of Education	**Number of respondents**	**Percentage of respondents**
Ph.D.	16	64
Ph.D. Candidate	5	20
M.Sc.	2	8
M.Sc. Candidate	1	4
Other Qualifications	1	4
Totals	25	100
Current Country	**Number of respondents**	**Percentage of respondents**
USA	16	64
Canada	3	12
United Kingdom	3	12
Other (France, Sweden, Germany)	3	12
Totals	25	100
Cause of Mass Extinction	**Number of respondents**	**Percentage of respondents**
bolide impact alone	5	20
terrestrial factors followed by bolide impact	18	72
Not sure and/or no mass extinction	2	8
Totals	25	100
Duration of Mass Extinction	**Number of respondents**	**Percentage of respondents**
Less than one hundred years	5	20
Hundreds to tens of thousands of years	3	12
More than ten thousand years	12	48
Not sure	5	20
Totals	25	100

Level of Education	**Number of respondents**	**Percentage of respondents**
Ph.D.	16	64
Ph.D. Candidate	5	20
M.Sc.	2	8
M.Sc. Candidate	1	4
Other Qualifications	1	4
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Current Country	**Number of respondents**	**Percentage of respondents**
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Less than one hundred years	5	20
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More than ten thousand years	12	48
Not sure	5	20
Totals	25	100

Duration of Mass Extinction	Ph.D.	Ph.D. Candidate	M.Sc.	M.Sc. Candidate	Other Qualifications
Less than one hundred years	3	1	2	0	0
Hundreds to tens of thousands of years	2	0	0	0	0
More than ten thousand years	10	1	0	1	1
Not sure	1	3	0	0	0
Cyril Galvin's Extinction Survey					
Bolide impact caused dinosaur extinction	5				
Bolide impact occurred but did not cause dinosaur extinction	51				
There was no bolide impact at K-T	12				
There was no mass extinction of vertebrates at K-T	32				
Response not indicated	18				
Total	118				
Hoffman and Nitecki Survey	Impact caused K-T M.E.	Impact occurred/did not cause M.E.	No impact	No M. E.	
Paleobiology subscribers	28	67	10	14	
British paleontologists	11	32	27	15	
German paleontologists	16	28	46	19	
American geophysicists	26	12	11	3	
Polish geoscientists	20	49	32	7	
Soviet geoscientists	2	7	4	5	

Duration of Mass Extinction	**Ph.D.**	**Ph.D. Candidate**	**M.Sc.**	**M.Sc. Candidate**	**Other Qualifications**
Less than one hundred years	3	1	2	0	0
Hundreds to tens of thousands of years	2	0	0	0	0
More than ten thousand years	10	1	0	1	1
Not sure	1	3	0	0	0
Cyril Galvin's Extinction Survey					
Bolide impact caused dinosaur extinction	5				
Bolide impact occurred but did not cause dinosaur extinction	51				
There was no bolide impact at K-T	12				
There was no mass extinction of vertebrates at K-T	32				
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American geophysicists	26	12	11	3	
Polish geoscientists	20	49	32	7	
Soviet geoscientists	2	7	4	5	