ON THE PATH OF DISCOVERY: THE CONTROVERSY AND SCIENCE BEHIND CHICXULUB CRATER

A MODE TO FURTHER UNDERSTANDING THE NATURE OF SCIENCE IN GEOLOGY

WYATT PETRYSHEN

CONTENTS

PREFACE

The below passages are a collection of narratives intended to further the understanding of the nature of science in geology. The main body *On the Path of Discovery*, brings the reader through a self guided tour of scientists conducting real-world research. Open ended reflection questions occur throughout the narrative to facilitate active discussions and to help develop an understanding in the nature of science. An activity is included to simulate the real-world research tasks conducted for the original scientific discovery. The section *Further Readings* has been put in place to expand on some of the scientific topics discussed in the case study. The *Further Readings* are written in a different tone then *On the Path of Discovery;* their main purpose is to clarify scientific topics. Acknowledgments and a detailed bibliography have also been included in this collection.

"I think it's much more interesting to live not knowing than to have answers which might be wrong. I have approximate answers and possible beliefs and different degrees of uncertainty about different things, but I am not absolutely sure of anything and there are many things I don't know anything about,… I don't have to know an answer. I don't feel frightened not knowing things, by being lost in a mysterious universe without any purpose, which is the way it really is as far as I can tell."

-Richard Feynman

ON THE PATH OF DISCOVERY: THE CONTROVERSY AND SCIENCE BEHIND CHICXULUB CRATER

A C T I : A M Y S T E R I O U S A S H

Steadfast and confident, Alan Hildebrand strides out of his graduation ceremony with a degree in hand. Having just completed his Bachelors degree in geology, an opportunity arose to work in the mineral exploration industry. It seems like a promising venture, so he takes it. Six years roll by, and the point comes where he wishes to further his education. Interested in Planetary Geology, Alan decides to undergo a set of placement exams for admission to a Ph.D. program. He preforms very well on the exams and awaits selection to an institution.

William Boynton, a geochemist and cosmochemist, invites Alan to the University of Arizona to join the Ph.D. program. Alan, who had lacked an innate path on where his study's would take him, accepts the invitation, effectively opening a new chapter in his life. Working mainly with tools used in determining the mineralogical compositions of rock samples, he begins to explore the breadth of their usefulness, acclimatizing himself to his new environment.

The tool of most interest was that of Neutron Activation Analysis (NAA); a non-destructive, quantitative tool used in determining the concentrations of trace elements in sample material. This tool was gaining popularity in the geoscience community, so much so, it was becoming an integral part in current research.

Of the most debated subjects in the geological community was a mysterious extinction period defined by the Cretaceous-Paleogene (K-Pg) geological boundary. This boundary, which represented a transition zone 65.5 million years ago, marked the point at which the non-avian dinosaurs and 75% of all species disappeared from Earth. Surviving into the present day are the mammals and avian dinosaurs (birds) that successfully transitioned through this zone.

Included in his first semesters courses, Alan starts a geochemistry course focusing on research topics of personal interest. Picking his brain, he recalls the current research by a team of geologists, geophysicists, and physicists led by Walter Alvarez on this mysterious extinction period.

An anomaly hidden in the K-Pg boundary had just been discovered in 1980, this work by Walter Alvarez had precipitated into a heated scientific debate amongst the communities of palaeontologists, geologists, and astronomers. The race to uncover an explanation for the creation of this boundary was starting to become a focal point in the paleontological community, and the search to uncover answers had begun.

The K-Pg boundary, which has been shrouded in mystery, was referred to as the Cretaceous-Tertiary (K-T) boundary in older publications. This boundary marked the period at which the non-avian dinosaurs, the ones we are all quite acquainted with, disappeared from the geological record. The K-Pg boundary highlighted an important dilemma in Science, how could such an extinction occur on a global scale? Leading scientists to validate their predictions, the absence of subsequent dinosaur fossil specimens above this emplaced layer confirmed to them a mass extinction had in-fact occurred; but they could not pin-point its cause. Speculation in the form of multiple hypotheses had begun to circulate in the late 1970s trying to provide the best casual explanation for the lack of fossils above this boundary, but no conclusive evidence could be drawn to support any one particular theory. How could such a successful group of animals (having existed for some 135 million years) suddenly go extinct, along with 75% of all other species? This was an important question that needed an answer. Pandemic diseases, global climate change, volcanism, and meteorite impacts all presented themselves with equal validity (Cleland, 2013). But which was correct? And how could we determine the best explanation?

Figure 1: The intermediate claystone layer separates the lower Cretaceous from the above Paleogene period (photo by Eurico

Think (1): As a Scientist, develop an idea to explain what caused the K-Pg mass extinction. What kind of evidence may be left behind for you to support your hypothesis? How does this vary between different causes of extinction (i.e., climate change, volcanism, supernovas, and extraterrestrial impacts)?

The K-Pg boundary is typically identified as a thin, millimetre to centimetre, globally distributed layer of clay that separates the Mesozoic from the Cenozoic time periods. Geologists use to identify the boundary as the Cretaceous-Tertiary boundary (K-T), but since the late 1990s, dropped the antiquated "Tertiary" for the designation Paleogene. Today the boundary is properly defined as the K-Pg, Cretaceous-Palaeogene periods, marking the end of the non-avian dinosaurs and 75% of all species. This mass extinction has been since the time of its discovery a topic of great debate and speculation. Gathering a collection of evidence to answer this question, the Alvarez team went about trying to calculate the rate at which this clay layer was deposited. *"The K-T boundary layers have a global distribution and are known from hundreds of localities making this the best known global timeline in the entire geological record with the exception of the present (Hildebrand,1992)."* Enlisting the help of his father, Luis Alvarez, a 1968 noble prize winning physicist in sub-atomic particle detection, Walter proceeded forward by sampling the K-Pg clay in the Gubbio region of Italy (Alvarez, 1997). Since the clay layer resides directly above the mass extinction event he could infer that the layer's deposition directly postdated the extinction. Via this inference he planned to create a timeframe on the duration of the clay's deposition, allowing for an estimation of the time that conditions were conducive for producing a mass extinction event.

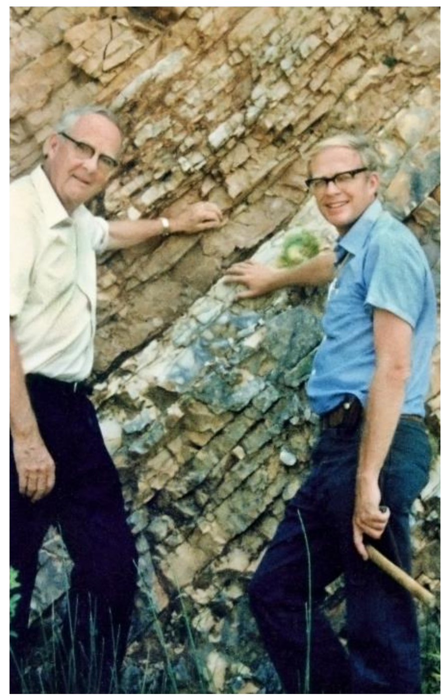


Figure 2: Luis (left) and Walter Alvarez at the K-Pg Boundary in Gubbio, Italy 1981

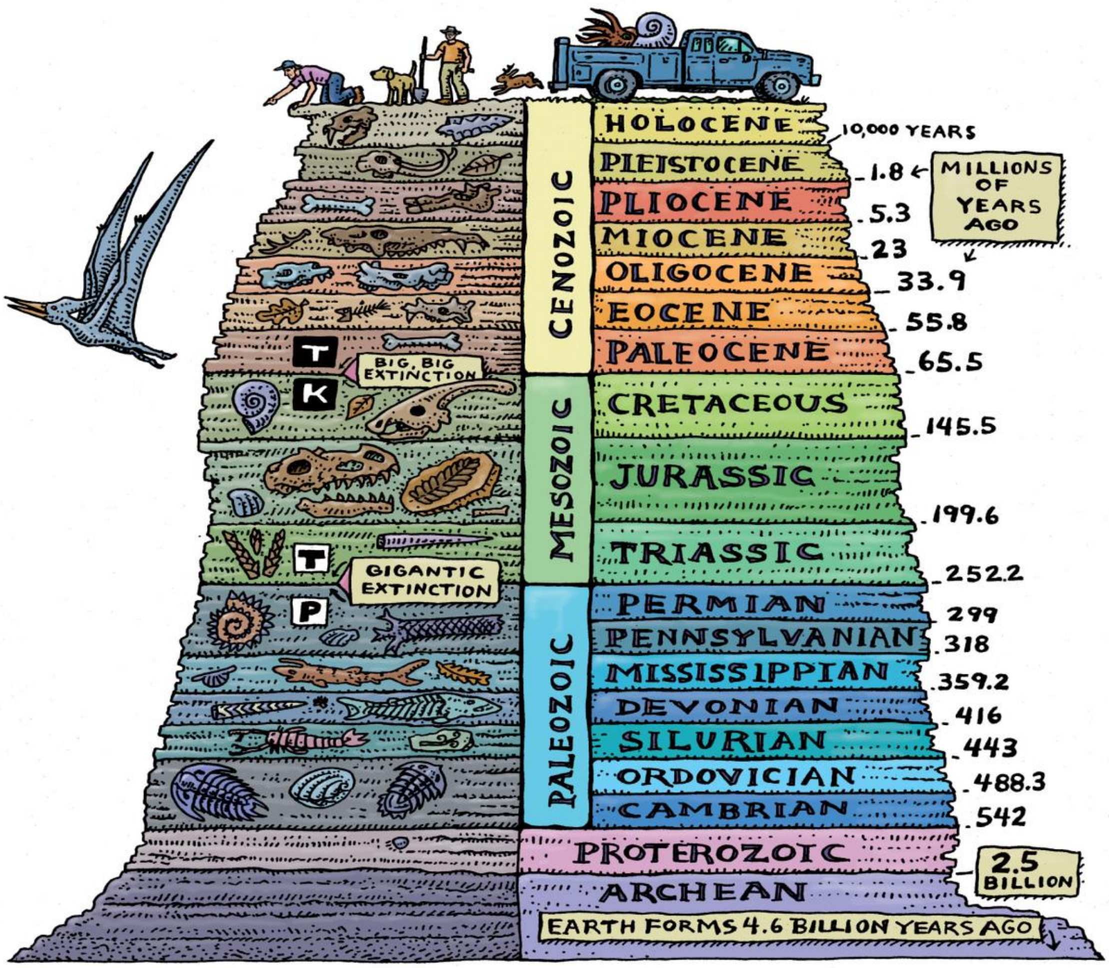


Figure 3: An artistic depiction of the geological time scale by Ray Troll

Raining in from space, small particles of meteoric dust reach the Earth's surface covering it at a continual rate, producing many thin layers distributed across the globe. This natural phenomenon continuing through to today was the key to the team's research. Assuming the processes they had planned to observe were in continuous operation throughout the geological record, they could successfully make inferences on the manner at which this boundary was formed. By analyzing the concentrations of this meteoric dust, conceivably, Walter could construct his time-scale for the time of deposition. The higher the concentration of meteoric dust, the longer the time of formation. Exploring this in 1980, using the modern tool of Neutron Activation Analysis, the team stumbled upon an unusually high concentration of iridium dust accumulated amongst the clays of the K-Pg boundary. Both rock units ambient to this clay layer displayed the very low iridium concentrations they had initially expected to encounter. Since iridium doesn't present itself in high concentrations at the Earth's surface, the team needed to continue their investigation into this mystery. By comparing samples of other crustal material distant from the K-Pg boundary, the clay layer continued to contrast the exceedingly low concentrations expected around 0.001 parts per million. This strange discrepancy was the first of a body of traces that they hoped would lead them to uncovering an explanation for the formation of this boundary layer.

Walter continued to sift and probe through the boundary samples with the hopes of finding an explanation to this anomaly. Alan, now reading this work almost a decade past, starts to realize the importance of this meaningful data. Intrigued, he precedes forward by opening his own investigation on the subject.

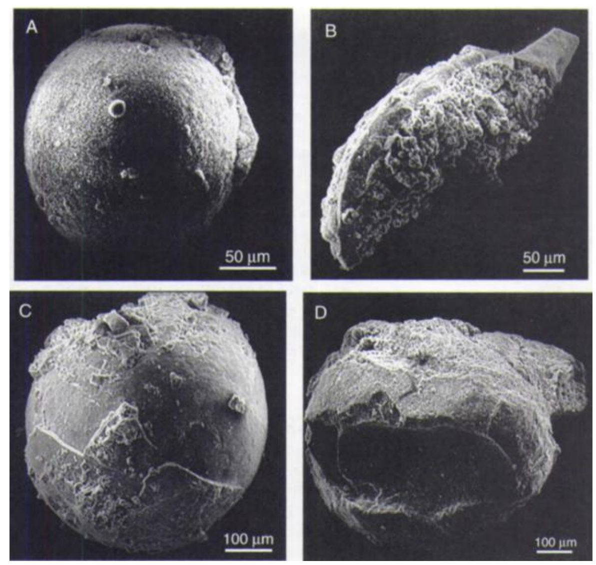


Figure 4: Spherules collected from the K-Pg boundary (Ortega-Huertas et al., 2002).

As Walter continued his research in Italy, a scientist by the name of Jan Smit uncovered another unusual iridium anomaly present in the K-Pg boundary. Residing in a sample from Corouaca, Spain, Jan collected and sent samples to an acquaintance working at the University of California, Los Angeles (UCLA) with the hopes of determining its mineralogical composition. Upon analysis he came across another unusual anomaly in the K-Pg boundary clay. Held within the pale brown clay, a collection of strange semi-glass beads, also known as spherules, resided. Small, under a millimetre in diameter, and spherical, their dark green glass-like texture contained tiny pits and grooves. With a strikingly close mineralogical resemblance to a mantle sourced rock (olivine, pyroxene, and calcium-rich feldspars), and not having a close enough physical resemblance to glass, Jan was left to believe the samples emerged from a volcanic source, similar in nature to the eruptions experienced in current day Iceland (Alvarez, 1997). In contrast, if the source material had instead been dominated by a more silica rich mineral, the beads would have been almost entirely glass. Jan was left to contemplate how their existence came to be (Alvarez, 1997).

To adequately explain the immense change in biota observed on either side of the boundary, a governing mechanism needed to be found; a mechanism that could conform to the predominant beliefs of the time and successfully account for all the traces contained in the rock record. Adding to this problem was the geological orthodoxy that only processes in current operation could account for the features experienced in the geological record (Uniformitarianism). This was known to geologists by the phrase "The present is the key to the past." Emphasized by Charles Lyell in 1887, a Lawyer and Geologist, it was a strict doctrine to describe Earth processes he had continually seen throughout his work. To account for the environmental variations on Earth, seen in both landscapes and species, only phenomena proceeding by small gradual changes could occur. Charles steadfastly argued the Earth can only change by these slow innumerable steps; millimetre by millimetre, year by year, eon by eon.

There are a number of rare elements that exist in low concentrations on Earth's surface. In contrast, they exist in high concentrations on extraterrestrial bodies and deep within the Earth's mantle. Walter and his fellow colleagues elected to postulate the K-Pg boundary formed from something much more radical than the paradigm of uniformity would allow. The clay layer implied to them that either a massive volcanic eruption or meteorite impact had occurred, neither of which conformed to the principles of uniformity. Walter, using the anomalous data collected by Jan, and his own work from Italy, formulated the explanation that a large bolide, an asteroid or meteorite, had struck the Earth causing tremendous environmental devastation and the subsequent dinosaur extinction. From the evidence they had found, it just made the most sense.

"The hypothesis that catastrophic impacts cause mass extinctions has been unpopular with many geologists, who have successfully employed the theory of 'Uniformitarianism' to model most geological phenomena" (Marvin, 1990).

"In Geology, it forced for the reevaluation of the central geological doctrine of 'Uniformitarianism' … which for 150 years had discouraged any thinking of catastrophic events" (Alvarez, 1990).

Think (2): How frequent do you believe such catastrophic volcanic eruptions or extraterrestrial impacts occur on Earth? Every year, every hundred years, every million years, every billion years? Give your reasoning.

As news started to circulate in the scientific community of Walter's impact-kill hypothesis, a resistance began forming, a skepticism, raising objections to his theory. If an impact had in-fact occurred, how could it remain hidden for so long? Scientists started to search for alternative explanations; explanations they thought better explained the K-Pg boundary extinctions.

Think (3a): Discuss the implications concerning your understanding of the process of science when confronted with the idea that scientists start looking for alternatives to the impact hypothesis because they do not like the impact hypothesis, and not because the data warrant another explanation.

Think (3b): If a large object impacted the Earth, wiping out major sections of life with it, what kinds of evidence would you need to support this hypothesis?

ACT II: AN UNCHANGED EARTH

"Men are born either Catastrophists or Uniformitarians. You may divide the human race into imaginative people who believe in all sorts of impending crises… and others who anchor their very souls to the status quo."

- Clearance King

From as early as we can see the human race has involved problem solving, be it from harnessing fire, creating aqueduct systems, to figuring out the age of our Earth, if a question has been asked or a problem put forth, we have either answered it, solved it, or at least tried to. For instance, when we first sought to discover the age of our Earth we enlisted the best tools at hand and set to work.

Drawn from chronologists' literal interpretation of religious scripture, scholars attempted to construct a biblically accurate date to when our Earth was created. This date would need to align itself with the churches ideology, supporting their idea of a human centered universe.

James Ussher, an Irish historian, scholar, and Protestant Archbishop was one notable example of a scholar attempting to formulate a time of creation for Earth (Rudwick, 2014). Described in his famous work, *Annales veteris testamenti, a prima mundi origine deducti* (Annals of the Old Testament, deduced from the first origins of the world), in the year of 1658, he calculated Earth's creation to have happened 4004 years before the common era. As time progressed, and new evidence came to light, scholars slowly started to more on the natural world for clues to the age of Earth as opposed to texts.

It was the gradually heavier reliance on observations of the natural world that helped early natural philosophers to Step outside the constraints created by religious. Most phenomena they saw in the world required a mechanistic cause. The wind uproots a tree and a river washes that tree down stream. These mechanistic causes would change the environment. An early natural philosopher, James Hutton, in 1795, concluded that Mechanistic causes currently in action also occurred in through history, leaving signs similar to those left by the same modern day processes. He asserted that "the present is the key to the past." As the discipline of geology emerged, individuals started to explore the idea of Earth's history. Using Huttons relationship it began to appear that not only did the Earth have a long history, but that humans were not around for most of that history.

Coined by Charles Lyell, *Uniformitarianism* was the answer to how we could interpret Earth's past and its change through time. Uniformitarianism stated that the operations in effect today are the same operations that were in effect in the past. This was a fundamental concept to early geoscience and was easily transferrable to other disciplines in Science. For Lyell, and by proxy, those who read is very popular text, uniformitarianism placed two constraints on interpretations of the past. First, that only causes, or processes that exist today have been at work through history. Second, Those causes or processes working in the past did so with no greater energy than what we experience in the present. When looking at some examples in geology, these claims lacked the power to explain anomalous stratigraphic features observed at geological boundaries. Examples include sharp stratigraphic boundaries and apparent mass extinctions.

An emergent explanation camefrom Georges Cuvier. It was calld *Catastrophism.*Still rooted in observations of the natural world Catastrophism proposed that Earth experienced intermittent and violent processes, changing the physical distribution of Earth's features rapidly. Because it was wrongly conflated with Biblical catastrophism, and because Lyell's wiritngs were so approachable to the public, geologists largely dismissed Catastrophism, asserting "Nature non facit saltus," (Nature does not jump). Edwin H. Colbert reiterates this strong bias in geology through the rivalry in the two schools of thought, *"Catastrophes are the mainstays of people who have very little knowledge of the natural world; for them the invocation of a catastrophe is an easy way to explain great events. But the modern student of nature is quite aware that the evolution of the Earth and the evolution of life upon the Earth have not proceeded by catastrophic events…"*

The concept of Catastrophism allowed the geologists who believed its rhetoric to interpret unconformities in strata as geological events of drastic change; unconformities that Uniformitarianism still struggled to adequately explain. Catastrophists saw this as a logical conclusion drawn from the presence of mass extinctions at the major geologic boundaries, however, a big issue still argued by Uniformitarians was the duration of time represented by these geologic boundaries. They argued, if processes such as erosion occurred at the boundaries, then the duration of time represented in the strata would seem greatly reduced. From this reasoning they maintained that because stratigraphic boundaries represented such vast expanses of time, sudden changes produced by catastrophic events couldn't adequately explain the global features encountered in the strata. The idea of drastic change could only explain minor features encountered in relatively small localities.*"If a record preserves only one step in a thousand, then truly gradual changes will appear to be abrupt" (Berggren, Van Couvering, 1984).*

By the early 1960s *Gradualism* had taken a firm root in the practice of geology; interpreting Earth processes as moving steadily forward allowing for small gradual changes to occur. However, like before, this definition still did not adequately explain mass extinctions and sharply defined stratigraphic boundaries. As Gradualism started to reaffirm itself in modern geology, new evidence was emerging identifying extraterrestrial (bolide) impacts as holding the potential to cause mass extinctions. This evidence was not conclusive, however..

This would change in 1960. Eugene Shoemaker, an American geologist, found, classified, and firmly established the stratigraphic indicators used in identifying extraterrestrial impact craters. His initial work was relegated to the Barringer Crater of Arizona, where he identified tektites and shocked quartz, amongst other things, as being ridged indicators of impacts. The discovery of these impact markers called for a re-evaluation of gradualism that incorporated both sudden changes and steady processes.

To adjoin these two very different theories on how the Earth operated, the shortfalls of Uniformitarianism and Catastrophism needed to be identified. Uniformitarianism was relatively nearsighted, it was incapable of looking past human's short life span as a point of reference (Palmer, 2003). In comparison, Catastrophism hadn't collected sufficient evidence as to validate its usage of large scale catastrophic events.

As time progressed into the 20th century, new ideas about the natural world progressed. Uniformitarianism's strict doctrine shifted to a more loose interpretation. Neo-gradualism emerged, detached from Uniformitarianism, the understanding of Earth processes morphed into the acknowledgment of sudden and catastrophic events occurring sporadically throughout time. These events have the ability to alter and change Earth in varying ways. This new view shifted from Charles Lyell's concrete laws and focused more wholly on Earths changes over time. These changes which dominated our current environment, can with the help of Neo-Gradualism, be linked synonymously to past events, successively helping scientists to interpret the rock record.

One large issue came forth from Catastrophism: Can catastrophic events, such as bolide impacts and volcanism, play large enough roles in facilitating drastic change in Earth processes? By the 1980s and 1990s geologists where still debating this topic; to large portions of the scientific community it still seemed unlikely catastrophic events could cause the recurring mass extinctions found in the rock record.

"Among the even less likely causes suggested for the death of the dinosaurs are poison gases, volcanic dust, meteorites, comets, sunspots, God's will, mass suicide (like lemmings!), and wars."
— Alan Charig

ACT III: A SMOKING GUN

According to the United States Geological Survey (USGS) 71% of the Earth is covered by the oceans and seas. Beneath this great blue expanse lays the oceanic crust which is composed of a variety of iron- and magnesium-rich basalt. Comprising this basalt are siderophile (iron-loving) and chalcophile (sulfur-loving) elements (Misra, 2012). In contrast, lithophile elements (silica-loving), which are relatively abundant in silica and aluminum bearing rocks and minerals, appear depleted in the oceanic crust. Using thiese differences allows one to discriminate continental from oceanic crust, proving important in distinguishing where a possible impact may have occurred.

Depending on an impactors locality, the impact will produce a set of unique products originating from its target rock. However, such cut and dry definitions do not always exist; evidence can still be lost and anomalies can still exist. Expanding on this concept of uncertainty is how the ocean floor is a diverse landscape of change, active tectonic processes recycle the ocean floor every 100 to 200 million years. With this in mind, if evidence of an ocean impact were to be found, a level of uncertainty would still exist stating that the crater might never be found. This is in part due to the ever changing ocean floor, and the fact we never actually observed the impact. The search for conclusive evidence supporting the impact-kill hypothesis will be murky at best.

Think (4): What type of evidence would you need to determine if an impact occurred on oceanic or continental crust? Make a list for both and think about their major differences.

Think (5): What evidence could be used to help find an impact crater location?

Alan Hildebrand, seeing the logic behind the impact-kill hypothesis, went about examining potential ejecta sites scattered across the globe. From the initial data collected, mainly the iridium anomaly, Alan wanted a larger body of evidence to either support the impact-kill hypothesis or contradict it. The evidence does not speak for itself, but reies on interpretation in light of guiding theory. If the impact-kill hypothesis was the best explanation, further evidence should exist to support it.

Impact ejecta is sediment produced from the impacting projectile and target material. A large impactor traveling very fast maintains a very high kinetic enerty. When that impactor hits a stationary object (like Earth) The enrgy is transferred to that stationary body and also converted to other forms of energy (sound, heat, etc.) Upon impact, a shock wave produced from the initial unloading of the projectile sets the target material into motion as ejecta (Osinski et al., 2013). This target material is subsequently deposited via a variety of different processes. Alan hoped by examining these potential ejecta sites he would interpret the clues to the location of an extraterrestrial impact of the right size and age to qualify as the “smoking gun” (Cleland, 2013) for the extinction of the dinosaurs.

Coming to Alan’s attention, in his search for further impact ejecta sites, were the deep sea drilling project (DSDP) reports from the past 20 years of the central Caribbean. Core samples of seafloor sediment and rock collected by expedition parties were brought to the surface for analysis. Hoping to shed light onto the distant geological past, the expedition strived to create a better understanding of our Earth. “The occurrence of basaltic ash … suggests further topographic disruption of the sea floor may have accompanied widespread basaltic eruptions in the central Caribbean” (DSDP, 1973).

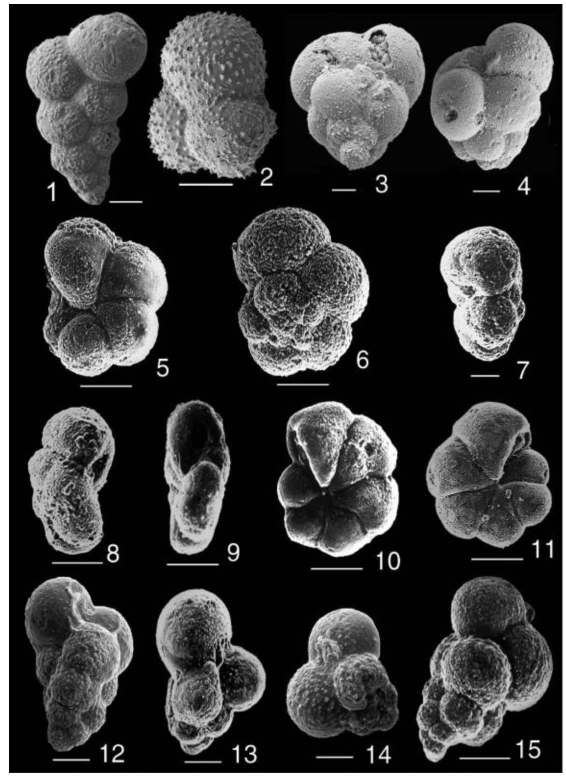
Florentin Maurrasse, a Ph.D. student graduating from Columbia University in 1973, had authored most of the Deep Sea Drilling Project reports around the Haitian Islands with a team of fellow scientists. Interpreting the deposits at the K-Pg boundary as “intraformational volcanogenic turbidite sites,” Florentin was convinced his interpretation of the stratigraphic products were best explained by a series of widespread basaltic eruptions at and around the time of the end-Cretaceous in the Caribbean region (Hildebrand & Boynton, 1990). This data seemed consistent through-out the central Caribbean, validating Florentin’s interpretation across all the DSDP sites in the area.

Basaltic ash and soot with an enrichment of Siderophile (iron-loving) elements started to become a common denominator amongst the potential impact ejecta sites. More over, the persisting ash and soot layer increased in thickness along the Eastern American coast. Hildebrand, reassessing the assertions made by Jan Smit in 1985, claimed, if an extraterrestrial impact had occurred it most likely struck somewhere along the Eastern American coast, and more specifically, somewhere in the Caribbean.

Despite these persistent traces of evidence that pointed towards an extraterrestrial impact, large portions of the scientific community still dismissed the possibility of an impact being responsible for the extinction. They instead favoured the volcanogenic interpretation of evidence. Hildebrand started to become bothered by this steadfast conviction to an old theory, a conviction that seemed to ignore newly discovered evidence. Hildebrand didn't want to believe scientists were purposefully disregarding evidence, but what better explanation could explain their lack of willingness to explore new theories. To him they were “behaving badly,” but that was something he could not let slow him down. He knew, the best way to support Walter Alvarez’s impact-kill hypothesis, was to find a crater (Hildebrand, Personal Communications, 2016). With this new objective in mind, he set out to re-examine the DSDP samples collected near the Haitian Islands, DSDP 151 and 153.

Contacting Florentin to re-examine the DSDP samples, 151 and 153, Alan waits in anticipation that Florentin will send the samples. Waiting becomes tedious and his desperation grows to provide more evidence to his theory; he knows if he wishes to see the samples he will need to put the initiative on himself. Destined for the University of Florida, Hildebrand travels on a personal vacation to gain access to the samples.

He starts to look through the initial reports, meticulously, methodically, combing through the physical evidence he finally held. “The samples originated from deep sea turbidite flows and widespread basaltic eruptions of the Central Caribbean” (8. Site 153 DSDP). “The recovered samples displayed intrafromational structures and basaltic ash.” “The Upper Cretaceous contains an erosional gap.” Is there a better explanation to encompass these initial observations made in the DSDP reports? He thinks so. The doubts he has in the initial reports continue to grow.



Think (6): What types of evidence would you expect to find from a deep sea basaltic eruption?

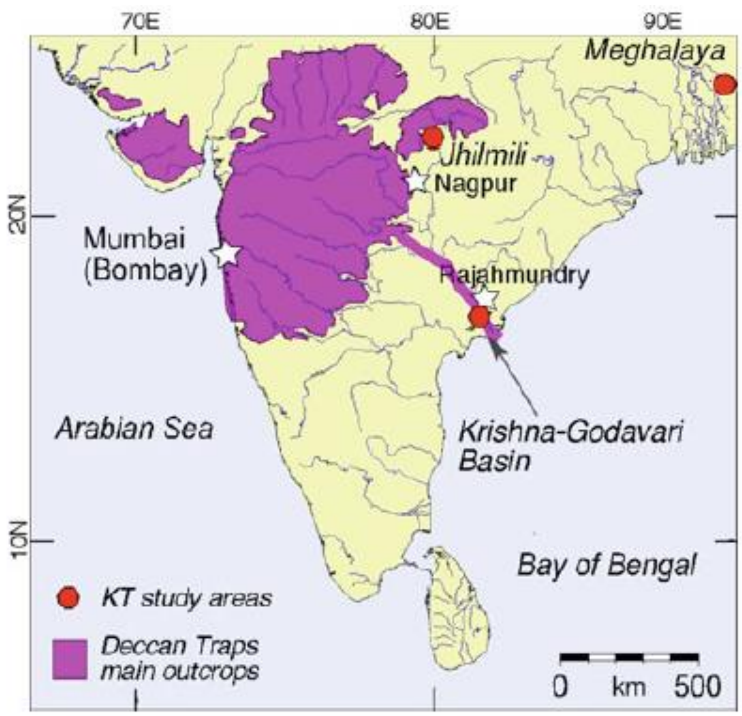
A cloud of aerosols and ash rise from the fire fountains of Kīlauea, 1983. Inadvertently, at the Mauna Loa Observatory located just above the Kīlauea volcano, airborne particulate collects on the air filters set up by scientists to observe particles in global circulation (Zoller, 1983). Analysis of the smaples of prticals taken from the filters yielded something completely unexpected. The iridium to aluminum ratio typically seen in Hawaiian basalts was 17,000 times the normal value in the Kīlauea samples (Zoller, 1983). Only a volcanic system being fed directly from the mantle could produce this kind of anomaly (Zoller, 1983).

Located in India, evidence for an ancient series of large scale volcanic eruptions exists, the Deccan Flood Basalts. The massive basaltic volcanos released over two million cubic kilometres of deep mantle plume material over a relatively short period of 500,000 years (Courtillot, 1990). The eruption period seemed to coincide with the deposition of the K-Pg boundary layer.

Gerta Keller, a young and enthusiastic palaeontologist working at Princeton University starts to conduct her own research and analysis on the faunal assemblages above and below the K-Pg boundary. Conducting her research on different planktonic foraminiferal species she observes a large shift in $\delta^{13}C$ sample values (ratio comparing organic carbon to inorganic carbon).

Figure 5: An image of marine organisms called planktonic foraminifera (Keller, 2012)

Organisms of all species want to conserve as much energy as possible, preferentially utilizing elements with the easiest broken bonds. Of the two main forms of carbon, C^{12} is the lightest and relatively easiest for organisms to use. During periods when organisms are abundant and thriving, they draw C^{12} from the environment effectively depleting the atmosphere in C^{12}; the opposite holds true for periods of extinction. Gerta Keller notices a drastic change in the ratios of C^{13}/C^{12} ($\delta^{13}C$) in sediment analyzed around the K-Pg boundary. A massive decline in organisms had occurred, but a slow one, one that had taken thousands of years (Keller, 1988). She was starting to wonder if the mass extinction boundary layer was facilitated by the eruption’s of the Deccan Flood Basalts. The recent research conducted on the Kīlauea volcano revealed iridium can be produced through the eruption of deep mantle plume material. It had also been shown some two million cubic kilometres of material was released from the Deccan flood basalts, leading to potential climate

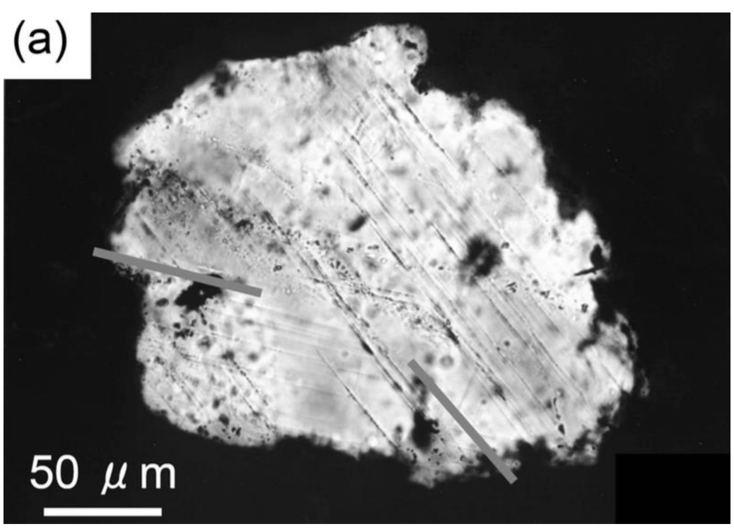


changing consequences via the release of soot and ash into the atmosphere. She could also see from her analysis of planktonic foraminifera that an extinction looked step-wise, lasting some thousands of years. The Deccan Flood Basalts were starting to become a very viable explanation to the evidence found in the rock record.

Figure 6: A map showing the main outcrops of the Deccan Traps (Keller, 2012).

Think(7): With two viable hypotheses providing superior explanation power for K-Pg mass extinction, the impact-kill hypothesis and Deccan flood basalt eruptions, how could we go about determining which provides the better explanation?

1988, along the confluent streams of the Brazos River in Texas, Joanne Bourgeois of the University of Washington, Seattle, combs through sections of sediment. With no immediate objective at hand it comes to her surprise when she finds an unusual coarse sandstone bed showing oscillatory wave patterns directly below the K-Pg boundary layer. By investigating these unusual sandstone beds, she interprets the oscillatory patterns as being current ripples possibly generated by a very large tsunami wave some 50 to 100 meters in height (Palmer, 2003). By deducing the amplitude of this tsunami wave from the ripple patterns found, her team concludes the wave originated either from the Gulf of Mexico or the Caribbean. Joanne supposes a large tsunami wave was created from an impact of a massive object.



Alan Hildebrand continues his process of reassessing the Haitian core samples. Through the re-examining process he starts to discover small fragments of quartz, tiny, with intersecting lamellae running through their structure. The more he continues to examine these samples the more he

Figure 7: A quartz grain showing planner deformation features (PDF's) (Nakano et al., 2008)

discovers these quartz grains, they were constituting about 1% of the total bulk material examined, they were abundant (Hildebrand, Boynton, 1990).

Most scientists believed that these intersecting lamella features encountered in the quartz grains were indicative of extremely high pressure conditions with relatively low temperatures. Basically, the intersecting lamellas were produced from the shock waves created by an impacting extraterrestrial object. The term 'shocked quartz' was adopted to describe these peculiar quartz grains.

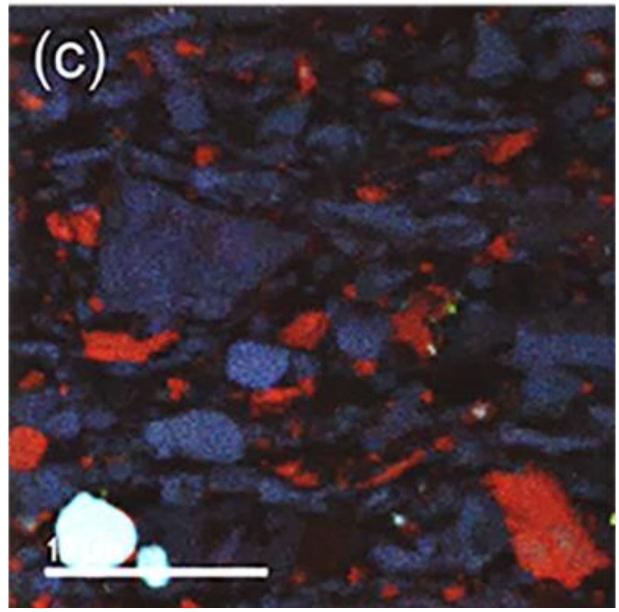


Figure 8: A Cathodoluminescent image of a quartz grains (gatan.com)

However, Carter and others in 1986 disagreed with this interpretation, stating the shocked quartz grains in the K-Pg boundary layer were most likely produced from "explosive" volcanic events; quite contrary to Alan's interpretation. How could anyone be sure their interpretation was correct?

Tests soon became created to answer these questions regarding the K-Pg boundary layer. To resolve the conflict surrounding the origin of the shocked quartz grains found in the K-Pg boundary layer, Cathodoluminescent imaging (CL) was instituted. Brown CL quartz is thought to be associated with quartz from low-grade metamorphic rock, while blue CL quartz is thought to originate from intrusive igneous to high-grade metamorphic sources (Owen and others, 1990). While looking at the samples of shocked quartz collected, they found the CL imaging revealed the lighter blue CL quartz associated with extrusive igneous events (volcanism) was almost completely absent from K-Pg boundary sand grains (Owen and Others, 1990). The test didn't conform with the "explosive" volcano interpretation, leaving only extraterrestrial impacts as the likely catalyst producing the shocked quartz grains.

Lithified in the Haitian core samples resided a coarse boundary deposit overlaying a stratigraphic gap of the Upper Cretaceous (Hildebrand, Boynton, 1990). The initial interpretation of this stratigraphic section, in 1973 by Florentin Maurrasse and his fellow team members, started to raise questions in Alan's mind. After having recently identified the shocked quartz grains in the layer directly above the stratigraphic gap, he thought an impact better explained the evidence he had found.

Something peculiar however arose from this discovery. In an attempt to maintain credibility, Florentin Maurrasse insisted he had previously identified these extraterrestrial impact traces, though this was never mentioned in the DSDP reports. Alan, wanting to avoid further conflict, acknowledged Florentin completed all the prior stratigraphic work, but reiterated, he had not at first connected the deposits to an impact event (Hildebrand, Personal Communications, 2015).

The pieces were starting to align in Alan's search to find concrete evidence supporting an extraterrestrial impact, but he knew for the impact-kill hypothesis to take a firm root in the scientific community it would need to provide the largest set of causal linkages for the evidence found; it would need to hold the greatest explanatory power (Cleland, 2013). Speculating from the evidence at his disposal, Alan presumes a large impact had occurred in the Caribbean region. The impact generated a massive tsunami wave which formed the stratigraphic gap experienced at the Upper Cretaceous, then, a rain of ash and soot darkened the sky, covering vast stretches of the region. He knew more evidence would need to be found, a smoking gun, something that could clearly adjudicate between these rival hypothesis (Cleland, 2013).

Short activity: List all of the evidence for catastrophic dinosaur extinction, and determine whether it supports an impact hypothesis or a volcanic hypothesis, or both. Does one hypothesis have more explanatory power than the other? Explain your answer.

ACT IV: A UNION OF EVIDENCE

“Much of the evidence held to be consistent with the former was also held consistent with the later”

-Palmer, 2003

By the late 1980s no one had yet gained the authority to judge the most powerful explanation for the end-Cretaceous mass extinction, but attitudes had shifted, favouring two hypotheses that continued to gain popularity. Both the asteroid impact and volcanic hypothesis imply that short-term catastrophic events are of great importance in shaping the evolution of life (Palmer, 2003). These two theories both possessed the best explanation for the evidence discovered, but still, more evidence was needed.

As time passes, more samples become available, adding weight to one of the hypotheses. Three lines of evidence slowly emerge convincing Alan further of the impact-kill hypothesis, pushing him closer to discovering an impact crater location. The first piece of evidence was a thin, 3 millimetre thick clay layer in the couplet of layers that encompasses the K-Pg boundary, the clay contained anomalously large amounts of siderophile, chalcophile, trace elements, shocked minerals, spherules, spinels, isotopic anomalies, and anomalously low amounts of lithophile elements (Hildebrand, Boynton, 1990). The presence of shocked quartz further supported the impact-kill hypothesis. Based on the thickness of the layers discovered, Alan Hildebrand starts to hypothesis a more specific location for an impact crater. Dating back to the conception of the atom bomb, teams had analyzed and closely observed the consequences and products of atomic experiments. One such observation was the distribution of material cast outward after an explosion. One scientist, H. Jay Melosh, had adapted the equations drawn from scientists studying explosive cratering and rendered the equations more accessible to extraterrestrial impacts on Earth. From these equations, hypothesized crater locations could be formulated from the thickness of ejecta blankets (material cast outward after an impact).

The second line of evidence found was that the maximum concentration of shocked minerals, and the largest grains of shocked minerals, only occurred in North America (Hildebrand & Boynton, 1990).

The third, and final line of evidence that pointed to an impact having occurred near North America, was the probable tsunami-wave deposits discovered in southern North America and the Caribbean region (Hildebrand & Boynton, 1990).

Two scientists, Thomas Ahrens and John O'Keefe, showed that giant tsunami waves produced by large impacting projectiles caused significant erosion of the deep ocean floor sediment within a few crater radii of the impact (Hildebrand & Boynton, 1990). More specifically, the equations gave Alan a way to analyze the probable impact-wave deposits he had found, providing him with the ability to narrow his search region. Alan, previously discovering the unconformities in the Haitian DSDP samples (Deep Sea Drilling Project), had formulated a general idea of where an impact could have occurred, but now he can narrow in on an actual location. He plugs the numbers collected from the analysis of presumed ejecta thickness sites into the newly generated equations. It renders that the most likely location for an impact crater is in a 1000 kilometre diameter circle in the area we today call Yucatan.

Figure 9: The dotted circle indicates the hypothesized

During a conference in Houston, Texas, Hildebrand serendipitousyhappens across a peculiar set of gravity profiles of the Yucatan area. The profile seems to show a structure that closely resembles a volcanic crater (Lopez Ramos, 1975) or an impact crater with associated extrusive material (Penfield and Camargo, 1981; Hildebrand et al., 1991). In a flurry of excitement he wishes to speak to the individual who first created the gravity profile. Needing the best tool at hand to track someone down, Alan grabs an old phone directory and starts flipping through the pages to find the name associated with the gravity profile, Glen Penfield. Alan picks up a phone and dials the number; the phone rings and rings.

Alan, reading up on Glen Penfield and the company that commissioned the gravity profiles, discovers that PEMEX, the state run oil company of Mexico, had hired an American consulting company to conduct magnetic imaging of the Yucatan area for petroleum exploration in 1978. An employee of the consulting company, Glen Penfield, was paired with a PEMEX employee, Antonio Camargo, to complete the assigned task. Both Glen and Antonio, after having analyzed the gravity images, discovered a large zone of crystalline rock in the Yucatan Peninsula, providing little to no economic potential for future petroleum development. Glen, intrigued by the findings, was prompted to share his work with the scientific community. Unfortunately, for the time being, he was forbade by PEMEX as they considered the findings proprietary information (Alvarez, 1997). Three years would pass until Glen and Antonio would receive the opportunity to present their work.

Presented at the Society of Exploration Geophysics in 1981, the two claimed a 180 kilometre diameter crater resided along a portion of the Yucatan Peninsula.

At first puzzled by the results, Glen Penfield "lit up" when he read of the asteroid collision theory arising from the discovery of the iridium-rich layer (Sky and Telescope, 1981). The bull's eye pattern featured in the Yucatan region looked distinctly like extraterrestrial examples that had been previously studied. No other mechanisms could explain the features encountered, even the andesitic rock (a composition inbetween the silica rich continental crust and the iron rich, silica poor oceanic crust) brought up in drilling seemed unexplainable by volcanic activity. The Yucatan and the surrounding area are relatively stable, lacking the volcanic activity to produce andesite. A common product of hypervelocity impact craters provides a better explanation for the andesitic rock found, allochthonous crater-fill deposits (impact melt rock). To the dismay of Glen and Antonio the presentation's discovery slowly fades from the minds of the scientific community. Since samples of the structure could not be readily obtained, conclusive support for their interpretation could not be validated, rather, it became forgotten. This little known discovery, however, was big for Alan, the path he had taken to confirming Walter Alvarez's impact-kill hypothesis was taking form.

Think(7): How large of a margin of error is acceptable when dating geological events? How close in age would an extraterrestrial impact or volcanic eruption need to be to an extinction event to be successfully correlated with its occurrence?

The advocates for terrestrial causes for the extinctions may seem to be party poopers, but the facts seem to lie on their side

-*Charles Officer*

1990, Alan publishes his first scientific paper describing the K-Pg boundary deposits and tsunami deposits in the Caribbean region. The paper discusses the creation of impact generated waves and the occurrence of a large impact atop oceanic crust (Hildebrand, Personal Communications, 2015). Editors of the journal find his interpretation of impact wave deposits to be inaccurate, dismissing the possibility of an impact occurring on oceanic crust (Hildebrand, Personal Communications, 2015). Disillusioned, this proves to him secondary lines of evidence still need to be found. This upcoming meeting with Glen Penfield is exactly what he needs.

Upon meeting with Glen and Antonio, Alan takes the opportunity to amass the required evidence needed in publishing a paper on this newly discovered impact crater. Wanting to give an appropriate name to this newly discovered crater, he looks to the small Mexican town residing on top of it. Separated by thick limestone beds, millions of years old, the town entitled Chicxulub, the 'The Devil's Tail,' becomes the newly adopted name for the crater. Submitting his work to the Journal of *Nature*, he and his fellow colleagues anxiously await the paper's reception. Carefully housed in the paper's meticulous and deliberate language he hopes to finally resolve the mystery shrouding the K-Pg mass extinction.

"There is no associative evidence linking the craters age to the K-Pg mass extinction," echoed the words of the editor. Communicated back to Alan, the message culminates a sense of disappointment and urgency to better elucidate his findings.

Alan, with his fellow team members, begins to brainstorm methods to address the reviewers comments. They realize they still need to find further physical evidence linking Chicxulub crater to the creation of the K-Pg boundary layer. But as luck would have it, the University of New Orleans came into the possession of a very decisive core sample, Yucatan-2, which originated from slightly outside the impact craters main region. Better yet, Antonio was also able to supply a crucial core sample, Yucatan-6, born from the very depths of the crater's impact breccia. With both of these recently discovered core samples in his hands, he hopes to unveil the impact structures lithology, pin-pointing an age to the impact crater.

Published in the September 1991 edition of *Geology*, Alan's findings were finally deemed acceptable to the scientific community. The paper was titled "Chicxulub Crater: A Possible Cretaceous/Tertiary boundary impact crater on the Yucatan Peninsula, Mexico." Despite the almost definitive evidence discovered by Alan linking the crater to the K-Pg mass extinction, a powerful sense of tentativeness was still palpable in the paper. Though tentative, Hildeprand still concludes the impact had occurred atop continental crust. Since the impact would have created such a large transient cavity, mantle material was brought to the surface and blast into the atmosphere where it recombined with siliceous material to create the strange spherules.

Think(8): Alan's ideas were initially rejected by the scientific community, despite this, when does an idea become scientific knowledge? What are the risks of continuing research on an idea experts deem misguided?

"The Chicxulub Crater is the largest probable crater on Earth. Its position and target-rock composition satisfy many of the characteristics required for the K-Pg crater, and it may have a K-Pg boundary age. This impact may have caused the K-Pg extinction (Hildebrand et al., 1991)."

Think(9): Why are definitive claims impossible to make for past events?

Alan was positive Chicxulub crater and the K-Pg mass extinction were correlated, but still an exact date could not be discerned for the crater's creation. In an attempt to verify its age, two outside scientists were enlisted to independently review the sample Yucatan-6. Gerta Keller, who was still strongly opposed to the impact-kill hypothesis, choosing rather to believe a volcanic eruption caused the mass extinction, and one other scientist were enlisted to examine the sample. She implemented the use of biostratigraphy to provide a relative age for the crater. Her investigation, and the investigation by the other scientist, independently found the samples resided from the late Palaeocene, a time much too young to coincide with the K-Pg boundary.

One might find it foolish to send samples to their most vocal opponent, but Alan saw it differently, he saw it as a way to strengthen his argument regarding the age of the crater (Hildebrand, Personal Communications, 2016). The plan however, backfired. The research paper published by Alan and his fellow colleagues entitled " Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico," found Gerta Keller's interpretation of the age invalid, citing the poor preservation of foraminifera in the limestone-marl unit of the sample Yucatán-6. Gerta would stand defiant against this claim, sticking to her initial convictions for the crater's age.

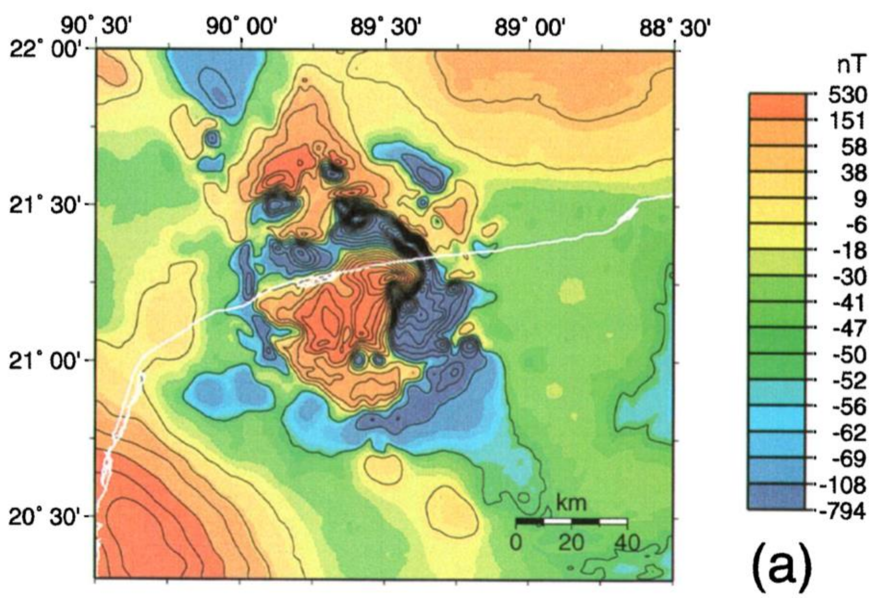
Think(10): How can the validity of the paper "Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico," be increased in light of the opinion from Gerta's interpretation?

Independently, after Alan's publication was released in *Geology*, a former editor for the Journal *Nature* published his own paper on the subject. Virgil Sharpton had conducted his own investigation on the crater's morphology and had formulated his own conclusions. Hot on the pursuit of other impact craters in Russia, Virgil held an intense interest in the formation of the K-Pg boundary. The "Gold Rush" had begun in discovering evidence linked to the end-Cretaceous mass extinction, everyone, everywhere, wanted a piece of the action and a piece of the fame.

Alan, using the newly collected gravity images from the Yucatan Peninsula, found the crater to be around 180 kilometres in diameter. A concentric high surrounded by two concentric lows defined the impact crater (Hildebrand et al., 1991).

Located on the dry land of Yucatán, local geological features further helped to provide proof of the crater's size. The circular structure of the crater was situated on both land and sea, residing beneath the permeable limestone of the area. Discovered by Kevin Pope, a strange geological feature remained along the crater's outer perimeter. Cenote (Ce-nō-te) , an assortment of sink holes and freshwater springs followed the entirety of the crater's outside ridge. Interpreted as having formed by major faulting after the impact, the overlying permeable limestone allowed water to percolate throughout its structure resulting in the pooling along fault scarps (Frankel, 1999).

Virgil Sharpton and Kevin Pope, using the distribution of cenotes and gravity images, estimated the crater stretched in size to around 300 kilometres in diameter. Both Virgil and Kevin suggested the outer blue and outer red sections of the image (see figure 10) represented the outermost ridge of the crater, effectively ballooning the radius of the crater from Alan's 90 kilometres to their newly supposed 150 kilometres. The loosely supported findings were then published. This was quite contrary to the rigours Alan's papers underwent, and started to slowly show how excitement over the end-Cretaceous mass extinction was making it easier to publish material on the topic. Of course, the media loved the notion of a much larger crater, implicating a larger catastrophe than what might have actually occurred (Frankel, 1999).



Alan was going to stick with his original conviction on the crater's size. Thinking differently from both Virgil and Kevin, he explained the distant outside red and blue features on the gravity profile existed in Yucatan's geology before the impact event. The cenotes observed around the crater also conjured different interpretations for Alan. He extrapolated that the cenote structures represented the outside ridge of the crater. Virgil had instead interpreted these structures as marking the border of the central uplift, drastically inflating the final size of the impact crater. These arguments however, were outside the original scope of what caused the end-Cretaceous mass extinction. As time passed into mid 1990s, a large following had amassed behind the impact-kill hypothesis in the scientific community, the Deccan Flood basalt hypothesis was losing steam.

Figure 10: Gravity profile of Chicxulub crater. The outside red and blue sections bordering the image represent Virgil Sharpton's and Kevin Pope's interpretation of the craters outer ridge(Pilkington, Hildebrand, 2000)

ACT V: THE EPILOGUE

As time advanced the practice of "argon-argon ($^{40}Ar/^{39}Ar$)" dating improved and became readily available for scientists to use. Since sample material of Chicxulub had finally been retrieved for analysis, Carl Swisher of UC Berkley had begun dating both samples of Chicxulub's crater and the Beloc Haitian deposits. Following the completion of the dating, Chicxulub crater exhibited a date of 64.98 ± 0.05 million years and the Haitian deposits exhibited a date of 65.01 ± 0.08 million years (Frankel, 1999). With almost identical dates, the previous analysis of the K-Pg boundary perfectly coincided with Carl's work. Finally, evidence of the impact's age had been concretely provided, helping to better convince others of the craters age and subsequent importance to one of the world's most famous mass extinctions.

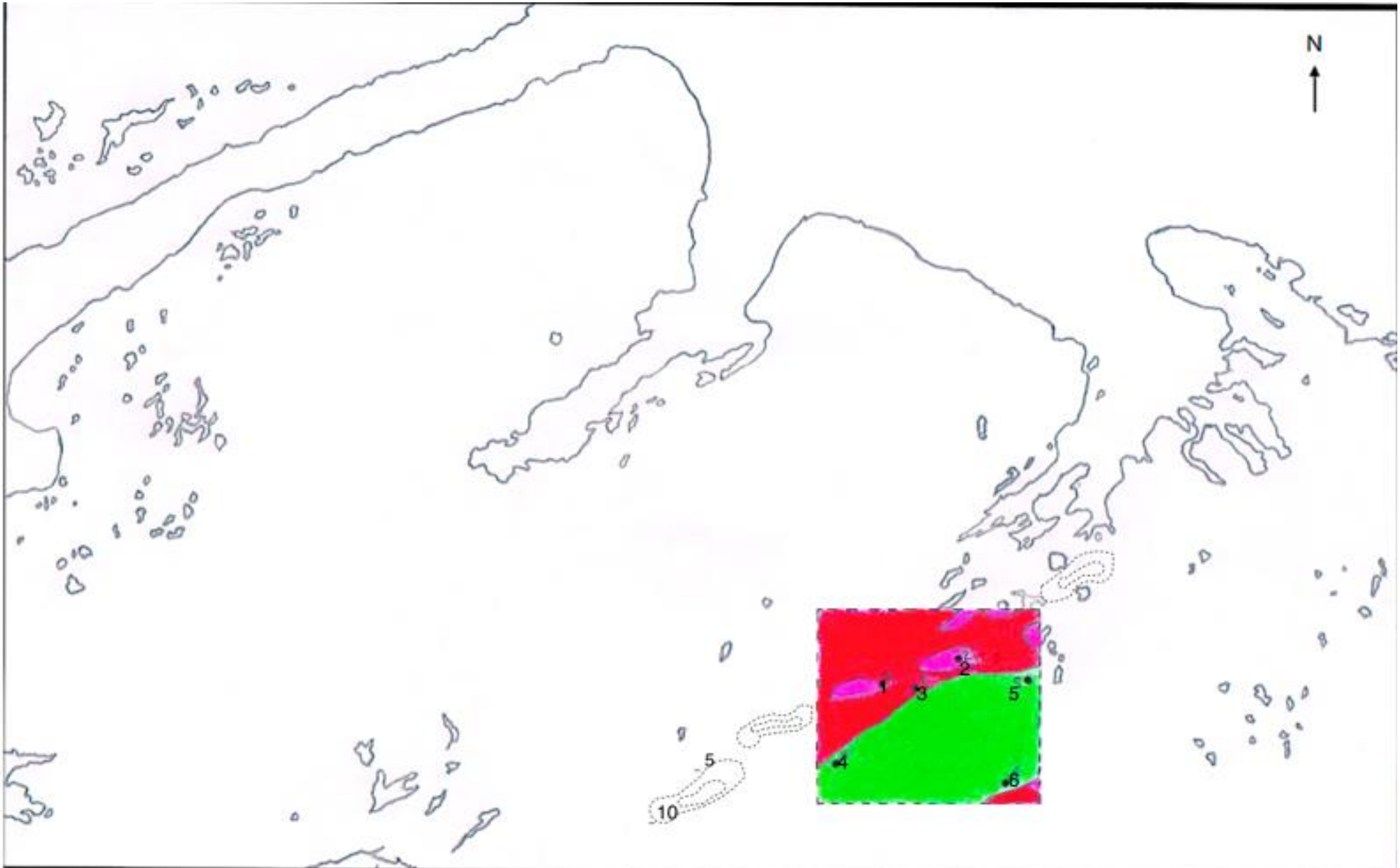
Despite the conclusion drawn from the "argon-argon" dating, doubt was still garnered from the opposition. A push against an impact caused mass extinction still persisted.

Alan had found his impact crater, he had found the final puzzle piece to solidify the impact-kill hypothesis; he hoped he had ended the debate that had raged on for years, but it wasn't that simple. Individuals and scientists, still argued against an impact caused K-Pg mass extinction. This however, was where a paradigm shift began to occur. Scientists started to attack the credibility of opposing scientists, slowly muddying their work and their image. “I don’t like to say bad things about palaeontologists, but they’re not very good scientists. They’re more like stamp collectors."-Luis Alvarez. Further evidence was found throughout the 1990s to better support the impact-kill hypothesis, but people, and more specifically the general public, saw the Deccan Flood Basalts as being a viable option.

Think(11): What role does the general pubic play in scientific debate? What kind of power does popular opinion have? Should it have any? How does it influence scientific exploration and scientific acceptance?

Here was where the final blow was dealt. In 2010, a collection of scientists published a paper declaring the K-Pg mass extinction as the resultant from the Chicxulub impact. The paper was titled “The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary,” and was authored by over 40 scientists. Alan Hildebrand once said, ‘that science is the act of putting hypothesis through a series of tests, the ideas and hypotheses that pass these tests are the ones that we should support.’ Science doesn’t always behave in this fashion, especially in Geology where we can never observe the phenomena we hope to explain (i.e., an event 65 million years ago), but we try to put our faith in the hypothesis that contains the greatest explanatory power (Cleland, 2013). Does this mean the Deccan Flood Basalts had absolutely no role in the mass extinction? Of course not, but the burden of evidence now resides on that side of the argument. A smoking gun could still remain undiscovered that would provide definitive support against the impact-kill hypothesis, but to this point it has not yet been discovered. Emerging in 2016 is discussion of a new and exciting hypothesis. A team of Japanese scientists in March of 2016 released a paper claiming the end-Cretaceous mass extinction was the result of a dark cloud encounter. The Earth passed through a dense cloud of particles that resulted in the final demise of the dinosaurs. Like the hypotheses before it, the dark cloud encounter could have occurred, but from the collection of evidence we have available today, the impact-kill hypothesis still provides the best explanation. Still, another paper was published on July 5 of 2016 stating the end-Cretaceous mass extinction was linked to both Deccan volcanism and the Chicxulub meteorite impact. The paper was entitled "End-Cretaceous extinction in Antartica linked to both Deccan volcanism and meteorite impact via climate change." As our tools and techniques improve in gathering and interpreting evidence, surely, new and better hypothesis will emerge to provide the best explanations. To further elucidate on this notion, in 2015, multiple scientific papers have been published hypothesizing that the Chicxulub impact may have triggered more then 70% of the Deccan Traps main-stage eruptions (Richards et al., 2015; Renne et al., 2015).

As scientists, we hope to discover and learn. Investigation into the end-Cretaceous mass extinction has resulted in a vast collection of multidisciplinary work between scientists in multiple disciplines. The opportunity to share, to learn, to grow as a scientist, should carry us all forward through the path of discovery; leading us to our own smoking gun and our own Chicxulub crater.



- Proterozoic Carbonate Limestone (750 Million Years)
- Intrusive Basalt (360 Million Years)
- Ordovician Carbonate Limestone (480 Million Years)

Scale 1:1,192,000

1	1.2
2	0.6
3	0.129
4	0.108
5	0.06652
6	0.045

Ejecta thickness collected in centimetres

t = 0.14(R)^(0.74) (x/R)^(-3)

t = thickness of ejecta
x = distance to crater
R = crater radius presumed at 25.032 km
All units for equation in meters

Imagine yourself as a junior geologist walking across the dissolute landscape of Canada's second largest island, Victoria Island. Located in Canada's arctic archipelagos, Victoria Island straddles the borders of Nunavut and the Northwest Territories.

Upon arrival to the island you are tasked with piecing together the potential location for an extraterrestrial impact you suspect occurred. To guide you in your inquiry, 6 bore holes were drilled, revealing different layers of ejecta material deposited in the strata. Having recently read a case study on the Chicxulub impact crater, you remember a series of scaling equations used in narrowing in on an impact crater location (Melosh, 1989; Osinski, Pierazzo, 2013).

The equations rely on the thickness of ejecta material found, the distance from the ejecta material to the crater, and the presumed radius of the impact crater. To aid you in finding the crater, the radius of the crater can be presumed at 3.75 kilometres.

During the activity, take note of the underlying lithology and topography your samples were collected from. Is there a potential for your sample thickness to be altered? If so, how could that conclusion be drawn, and what mechanism could be behind it? Are there associated complications with using this technique, and what problems might be associated with it?

Included on the activity map are the bore holes numbered 1 from 6, along with their respected ejecta thicknesses. Both the lithology of units, and equation used in solving for the distance to the crater are provided. All variables used in the equation must be in meters and converted accordingly. Your objective when manipulating the equation will be to solve for the unknown variable, then accurately transfer that data to the given map. From this you should be able to determine a general location for where an impact likely occurred. The supplies required to complete with activity are: a basic scientific calculator, a ruler, pieces of string.

FURTHER READINGS

A STRANGE ANGLE

A Strange Angle hopes to elucidate on the continuing arguments experienced throughout the scientific community. This is just one of the many issues arising from the scientific debate on the K-Pg mass extinction and the Chicxulub impact crater.

Like a stone skipped across a pond or dropped from a bridge, the trajectory at which an object impacts a surface will dictate the features of its crater. Proposed at the early conception of Chicxulub's discovery, Alan Hildebrand had asserted with utter conviction the impact occurred at a 45 degree angle. Depending on the mass, speed, diameter, density, angle, and lithology of target rock, the impactor and target played specific roles in the crater's formation.

From the early discovery of the crater it had been presumed the diameter of the bolide ranged around 10 kilometres. Relative to the composition of the bolide, the diameter at which near identical crater features would be preserved start from around 12 kilometres for a comet to 10 kilometres for an asteroid. Since no living creature survived to record the size of the bolide, observing crater features such as depth, diameter, and ejecta distribution can lead scientists to deduce the diameter of the impacting bolide.

Alan Hildebrand, in his 1995 paper, described the morphology and processes governing the formation of Chicxulub. As craters increase in size, they undergo a gravity driven modification where the floor of the initial transient cavity rebounds upwards, and the crater margins collapse inwards, to form broad, shallow, complex craters. As the size increases further, this central peak is replaced by a peak ring, typically an irregular ring of hills and massifs, that lack prominent asymmetrical boundary scarps.

With the continued investigation into the morphology of Chicxulub, it could be said with certainty, the crater measured 180 kilometres in diameter and formed a multi-ring basin (Hildebrand, 1995). Defining the craters structure is distinctive asymmetries revealing an elongate central gravity high (**trending northwest**) encircled by a horseshoe-shaped gravity low (Hildebrand, 1991; Sharpton, 1993; Schultz, D'Hondt, 1996). Continuing to interpret the evidence collected from the gravity mapping surveys, from the distribution of the ejecta blanket and general morphology of the crater, Alan Hildebrand concluded the bolide impacted at around a 45 degree angle. Any irregular anomalies encountered in Chicxulub's structure could be explained from the depth at which the transient cavity reached after excavation. From implementing scaling laws, Alan was able to formulate the transient cavity reached a depth of around 35 kilometres, with the maximum excavation depth reaching 12 kilometres (Morgan et al., 1997). Since the depth of the transient cavity reached such extensive depths, subsequent faulting and slumping would have quickly filled the gaping hole, creating the multi-ring basin we observe today.

A limiting factor continuing to hamper investigative procedures was the limited accessibility to samples. With approximately half of Chicxulub crater being submerged by water, gaining access to new samples for analysis cost astronomical amounts, amounts inaccessible to the team. Despite this hindrance, the team would forgo their limitations and piece together tangible conclusions.

Peter Schultz, a Ph.D in astronomy, became Associate Professor in the Department of Geological Studies at Brown University in 1984. Having completed various projects with NASA, Peter Schultz was promoted to the Science Coordinator at the NASA Ames Vertical Gun Range, which conducted experiments on the ballistic trajectories of crater forming processes. In 1996, Peter Schultz, with the help of Steven D'Hondt from the University of Rhode Island, published a paper in the journal of *Geology* claiming the Chicxulub impact occurred at an oblique angle of 20-30 degrees instead of the previously though 45. Rooted to the proposed claims was the asymmetrical geophysical signatures first discovered by Alan Hildebrand. Since Chicxulub's structure exhibited distinctive asymmetrical features, Peter Schultz postulated from the ballistic trajectory experiments done in lab, an oblique impact best explained the features created. From Hildebrand (1991) and Sharpton's (1993) prior papers, the gravity maps revealed an elongate central gravity high encircled by a horse-shoe shaped gravity low. Peter Schultz, continuing to instrument in lab models to interpret the crater, speculated that the bolide impacted from the Southeast sending a vast vapour cloud of rock hurling to the Northwest. To provide support for his claims he turned to observing the distribution of ejecta material across North America. In his 1996 paper, Peter Schultz stated there was a presence of less-shocked crystalline basement material downrange from the impact, greater preservation of meteoric spinels due to decreased pressure from the oblique impact angle, larger overall shocked quartz grains, and thicker two component layers in North America.

A consequence of the oblique angle as further told by Peter Schultz are the environmental repercussions created from the vapour cloud of melt rock launched towards North America. Due to the force of the impacting object at the 20-30 degree angle, the vast majority of excavation material would have been launched down range from the incoming trajectory. Being hot enough to instantaneously combust plant material, the produced vapour cloud destroyed everything along its path except some extremely lucky aqueously submerged organisms (Schultz, D’Hondt, 1996).

Stored in the sediment, preserved in time, was the pollen from regrowth after the impact had occurred and the climate had returned to a semi-hospitable state. Retrieved from the pollen samples were astonishingly large amount of fern spores. Fern is a naturally advantageous species that can quickly colonize areas reduced in species competition and deficient in mineral nutrients. This perceived ‘Fern Spike,’ indicated to Peter Schultz that North America had experienced the most environmentally devastating consequences after the impact, resulting in a much larger extinction rate then anywhere else on the globe (Schultz, D’Hondt, 1996). A ‘Fern Spike’ was also discovered off the coast of Japan, one small, seemingly unrelated discrepancy amongst the pollen analyzed. This however didn’t dissuade Schultz. The almost complete biota extinction of North America proved to Peter Schultz that the oblique impact hypotheses was true.

Many controversies and arguments had arisen from the discovery of Chicxulub crater, publicized from the media, the dinosaur extinction garnered massive attention from the general public. The issue with this publicity was the potential for pseudoscience to become intertwined with the legitimate work being conducted by scientists like Peter Schultz and Alan Hildebrand. The gold rush for evidence brought about by the discovery of Chicxulub crater and the allure of dinosaurs had casted a lot of doubt on the validity of opposing arguments, diminishing the explanatory power for some scientific theories.

NEUTRON ACTIVATION ANALYSIS

The process of Neutron Activation Analysis requires a small sample of material to become sealed in a polyethylene or silica fused tube, suspended in the core of a nuclear reactor, and bombarded in a sea of neutrons (Muecke, 1980). Reacting only with a small number of atoms, the neutrons produce radioisotopes of the parent isotope present. Relative to the abundance of elements comprising the sample, each of the elements occurring possess a unique likelihood of receiving the neutron. Characterized by its neutron capture cross section, elements with larger cross section value will more readily form radioisotopes.

Hoping to better illustrate this, if a soil sample containing both magnesium and sodium are prepared for analysis, and the magnesium present in the soil has a much greater ratio then that of the sodium. The element that can more readily accept the incoming neutron will show up to a greater extent then the element that does not. Henceforth, if the Sodium better receives the neutron, it will have a larger ratio of radioisotopes in the sample then the magnesium (Hildebrand, Personal Communication, 2016).

From the new daughter isotopes formed, each possesses a characteristic energy and unique half-life related to its stable form. Quickly preceding the formation of the daughter isotope, the sample is transported to the lab to undergo radio assay, the detection of decaying nuclei. Through the process of half-life measurements or gamma ray spectrometry the radioisotopes are identified. The identity of the daughter isotope will reveal that of the parent isotope during analysis. To obtain the desired quantitative data, the quantity of parent isotope is observed by the decays of related daughter isotopes present. For a successful analysis to occur, the daughter isotope must have a large enough half-life as to not decay before detection, and also a short enough half-life so that the detection can occur in a relatively small amount of time (Muecke, 1980).

When Neutron Activation Analysis occurs a relatively stable form of the radioisotope needs to be chosen to ensure the above criteria is met. Iridium, with a large thermal neutron absorption cross section, has 2 naturally occurring isotopes and 34 lab constructed radioisotopes. To perform the detection tests, the activation of iridium 191 begins. Attaching itself to the atom, the newly collected neutron transforms the stable iridium 191 into the unstable iridium 192, which then later decays to the parent isotope. Possessing a 73.83 day half-life period, ^{192}I provided both the appropriate qualitative data and half-life period. Comparatively, iridium's remaining radioisotopes have half-lives ranging from 24 hours to a few seconds, making the data collection almost impossible. Via this technique the iridium anomaly was discovered.

TEACHING NOTES

ACKNOWLEDGEMENTS

I would like to give my sincere gratitude and admiration to my professor and supervisor, Glenn Dolphin, of the University of Calgary. He has shown me the upmost level of respect and patience throughout the writing process, sinking many hours to editing and guiding me towards success. I would like to thank to my fellow research assistants Simon Wiebe, Jessica Burylo, and Emily Hurst, for always providing constructive feedback and an accommodating and welcoming team work environment. A big thanks to Alan Hildebrand who found the time and patience to meet with me on multiple occasions, providing insight and a first hand account to the details surrounding Chicxulub crater.

This case study was a part of a larger project of historical case study development generously funded by the Taylor Family Foundation for Teaching and Learning, and the Tamaratt Professorship in Geoscience.

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