Asteroids and dinosaurs: Unexpected twists and an unfinished story

Plate tectonics might seem like a routine topic from a 7th grade textbook, but in the 1970s, plate tectonics was cutting-edge science. The theory had only gained widespread acceptance over the previous ten years and subsequently attracted scads of scientists looking to open up new intellectual frontiers. Walter Alvarez was one of them, but his research into plate tectonics was destined to be sidelined. An intriguing observation would eventually lead him, his collaborators, and the rest of science on an intellectual journey across geology, chemistry, paleontology, and atmospheric science—towards solving one of the great mysteries in Earth's history: What happened to the dinosaurs (Fig. 1)?

Fig. 1. At left, Luis and Walter Alvarez stand by the rock layers near Gubbio, Italy, where unusually high traces of iridium were found at the Cretaceous-Tertiary boundary. Was this evidence that of an ancient supernova or an ancient asteroid impact? And what, if anything did it have to do with the dinosaur extinction?

This case study highlights these aspects of the nature of science:

- Science can test hypotheses about events that happened long ago.
- Scientific ideas are tested with multiple lines of evidence.
- Science relies on communication within a diverse scientific community.
- The process of science is non-linear, unpredictable, and ongoing.
- Science often investigates problems that require collaboration from those in many different disciplines.

From plate tectonics to paleontology

One of the key pieces of evidence supporting plate tectonic theory was the discovery that rocks on the seafloor record ancient reversals of the Earth's magnetic field: as rocks are formed where plates are moving away from one another, they record the current direction of the Earth's magnetic field, which flip-flops irregularly over very long periods of time (Fig. 2). In these "flip-flops," the polarity of the magnetic field changes, so that a compass needle might point south for 200,000 years and then point north for the next 600,000 years. Walter Alvarez, an American geologist, and his collaborators were looking for independent verification of the timing of these magnetic flip-flops in the sedimentary rocks of the Italian Apennine mountains. Around 65 million years ago, those sediments lay undisturbed at the bottom of the ocean and also recorded reversals of the magnetic field as sediments filtered down and were slowly compressed over time (Fig. 2).

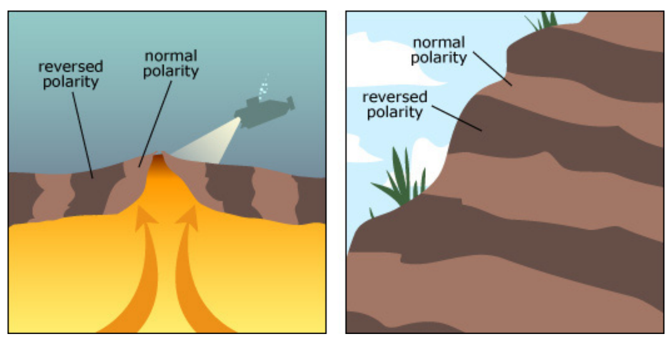


Fig. 2. As new seafloor forms, the igneous rock records the current state of the Earth's magnetic field. Sedimentary rock layers forming at the bottom of the ocean may also record these magnetic flip-flops as sediment layers slowly build up over time. Alvarez studied such sedimentary rocks that had been uplifted and are today found in the mountains of Italy.

As Alvarez clambered up and down the Apennines, collecting samples for magnetic analysis, he regularly confronted a distinct sequence of rock layers marking the 65 million year old boundary between the Cretaceous

Luis and Walter Alvarez photo from Ernest Orlando Lawrence Berkeley National Laboratory; supernova image courtesy of NASA/Swift/S. Immler; asteroid impact image courtesy of NASA Ames

and Tertiary periods—the "KT" boundary (from Kreidezeit, the German word for Cretaceous). This boundary was made up of a lower layer of sedimentary rock rich with a wide variety of marine fossils, a centimeter-thick layer of claystone devoid of all fossils, and an upper layer of sedimentary rock containing a much reduced variety of marine fossils (Fig. 3).

Why the sudden reduction in marine fossils? What had caused this apparent extinction, which seemed to occur so suddenly in the fossil record, and was it related to the simultaneous extinction of dinosaurs on land? Alvarez was curious and recognized that answering such a difficult question would garner the respect and attention of the scientific community.

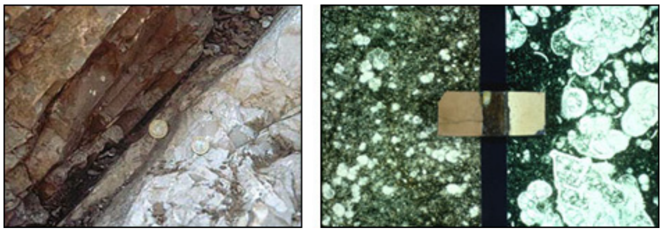
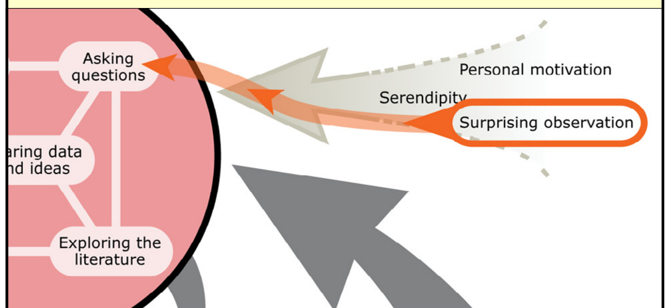


Fig. 3. The Cretaceous-Tertiary boundary, as recorded in the rocks at Gubbio, Italy. At left, the later Tertiary rocks appear darker—almost orange—and the earlier Cretaceous rocks appear lighter when viewed with the naked eye. At right, magnification reveals few different sorts of microfossils in the Tertiary layers, but a wide variety in the Cretaceous sample (far right).

Walter's scientific journey so far:



While examining evidence related to plate tectonic theory, Walter makes an intriguing observation, which inpires him to ask questions about the KT extinction.

False starts and a new lead

At the time, most paleontologists viewed the dinosaur extinction as a gradual event capped by the final extinctions at the end of the Cretaceous. To Alvarez, however, the KT boundary certainly looked catastrophic and sudden—but the timing of the event was still an open question: was the KT transition (represented by the clay layer in the stratigraphy) gradual or sudden? To answer that question, he needed to know how long it had taken to deposit the clay layer—but how could he time an event that happened 65 million years ago? Walter Alvarez discussed the question with his father, the physicist Luis Alvarez (Fig. 4), who suggested using beryllium-10, which is laid down at a constant rate in sedimentary rocks and then radioactively decays. Perhaps beryllium could serve as a timer.

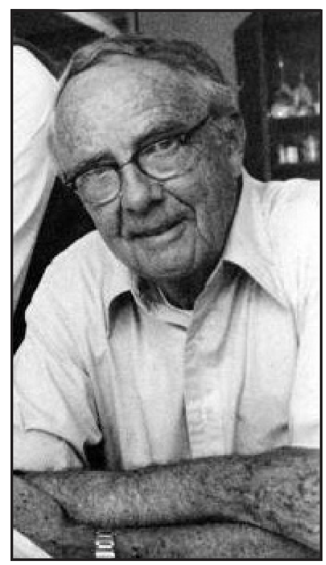


Fig. 4. Luis Alvarez was awarded the Nobel Prize for physics in 1968.

Their idea was to recruit Richard Muller, another physicist, to help measure the amount of beryllium-10 in the clay layer, correct for how much the beryllium would have decayed since then, and then reason backwards to figure out how many years would have had to pass for that much beryllium to be deposited. However, before they could take the beryllium measurements, they learned that the published decay rate for the isotope was wrong. Calculations based on the new numbers revealed that the planned analysis would not work. For the amounts of beryllium that they could detect, the timer in the 65 million year old clay layer would have already run out—all of the beryllium would have decayed away.

The beryllium investigation turned out to be a dead end, but Luis Alvarez soon came up with a replacement: iridium. Iridium is incredibly rare in the Earth's crust but is more prevalent in meteorites and meteorite dust.

Gubbio, Italy rock layers by Frank Schönian; thin section under magnification by Alessandro Montanari; Luis Alvarez photo from Ernest Orlando Lawrence Berkeley National Laboratory

They reasoned that since meteorite dust and hence, iridium, rain down upon Earth at a fairly constant rate, the amount of iridium in the clay would indicate how long it took for the layer to be deposited. An observation of more concentrated iridium (around one iridium atom per ten billion other particles) would have implied slower deposition, and less iridium (an undetectably small amount) would have implied rapid deposition and a sudden KT transition, as shown below (Fig. 5).

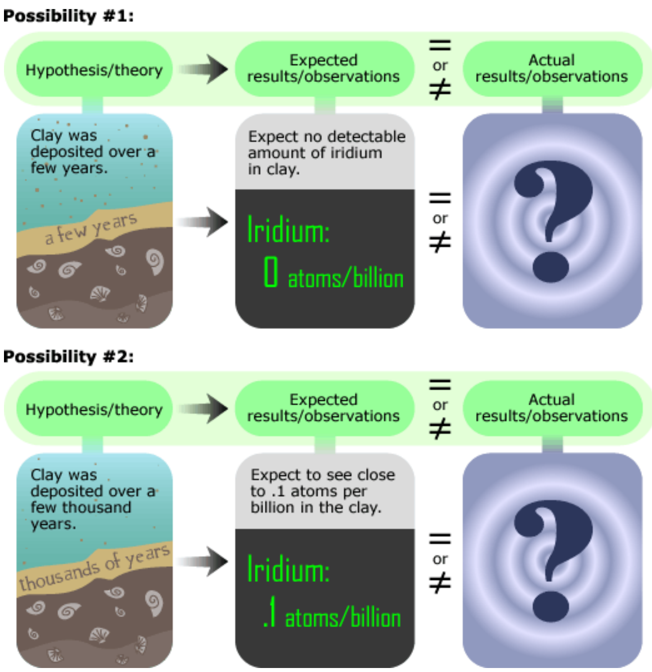
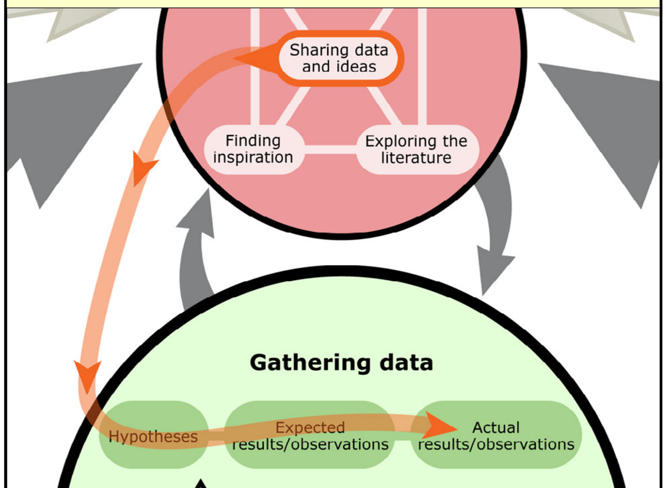


Fig. 5. Using iridium to test ideas about the clay deposition.

Walter's scientific journey so far:



Walter wants to know if the KT transition was gradual or speedy. Discussions with peers eventually lead his team (after a false start) to the idea that iridium could indicate whether the hypothesis of a gradual deposition or the hypothesis of a speedy deposition was more accurate.

The plot thickens ...

The results of the iridium analysis were quite clear and completely surprising. The team (which also included chemists Helen Michel and Frank Asaro; Fig. 6) found three parts iridium per billion—more than 30 times what they had expected based on either of their hypotheses, and much, much more than contained in other stratigraphic layers (Fig. 7)! Clearly something unusual was going on at the time this clay layer was deposited—but what would have caused such a spike in iridium? The team began calling their finding "the iridium anomaly," because it was so different from what had been seen anywhere else.

Fig. 6. Helen Michel and Frank Asaro with Walter and Luis Alvarez.

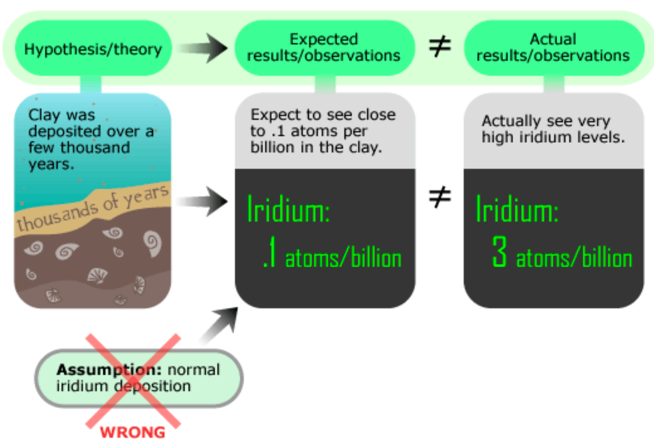


Fig. 7. A surprising finding reveals a faulty assumption.

Now Alvarez and his team had even more questions. But first, they needed to know how widespread this iridium anomaly was. Was it a local blip—the signal of a small-scale disaster restricted to a small part of the ancient seafloor—or was the iridium spike found globally, indicating widespread catastrophe?

Alvarez began digging through published geological studies to identify a different site that also exposed the KT boundary. He eventually found one in Denmark and asked a colleague to perform the iridium

Helen Michel, Frank Asaro, Walter and Luis Alvarez photo from Ernest Orlando Lawrence Berkeley National Laboratory test (Fig. 8). The results confirmed the importance of the iridium anomaly: whatever had happened at the end of the Cretaceous had been broad in scale.

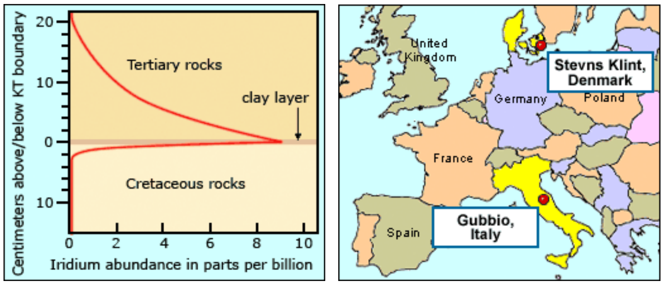
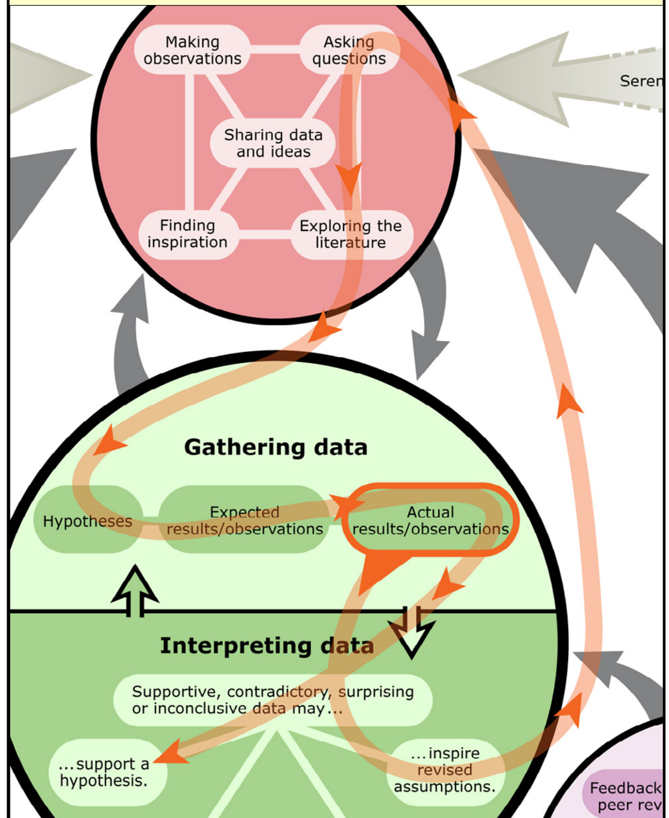


Fig. 8. At left, a simplified graph showing iridium content across the KT boundary as measured at Gubbio, Italy. Follow up work suggested that the clay layer actually contained even more iridium than their first test had suggested—10 parts iridium per billion! At right, Gubbio, Italy and Stevns Klint, Denmark—sites which confirmed the widespread presence of an iridium anomaly.

Walter's scientific journey so far:



A completely surprising test outcome prompts Walter and his team to ask new questions. Using published studies, Walter identifies a new site for testing and confirms his original results.

Another false start

Alvarez had embarked on the iridium analysis to resolve the issue of the speed of the KT clay deposition, but the results sidetracked him once again, pointing to a new and even more compelling question: what caused the sky-high iridium levels at the KT boundary? The observation of high global iridium levels happened to support an existing hypothesis.

Almost ten years before the iridium discovery, physicist Wallace Tucker and paleontologist Dale Russell had proposed that a supernova (and the accompanying radiation) at the end of the Cretaceous had caused the extinction of dinosaurs. Supernovas throw off heavy elements like iridium—so the hypothesis seemed to fit perfectly with the team's discovery (Fig. 9). In this case, an observation made in one context (the timing of the KT transition) ended up supporting a hypothesis that had not initially been on the researchers' radar screen at all (that the dinosaur extinction was triggered by a supernova).

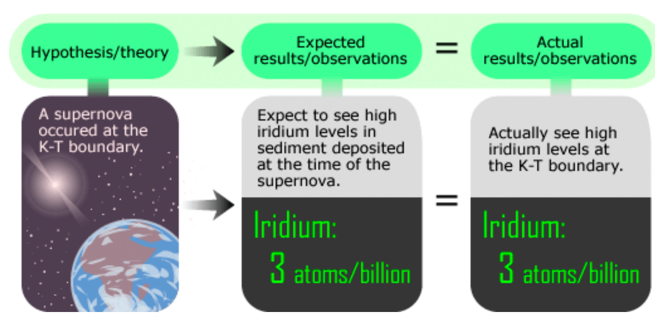


Fig. 9. The iridium observation supports the supernova hypothesis.

To further test the supernova hypothesis, the team reasoned out what other lines of evidence might be relevant. Luis Alvarez realized that if a supernova had actually occurred, it would have also released plutonium-244, which would have accumulated alongside the iridium at the KT boundary.

Excited about the possibility of the supernova discovery (strong evidence that the dinosaurs had been killed off by an imploding star would have made worldwide headlines), the team decided to perform the difficult plutonium tests. When Helen Michel and Frank Asaro came back with the test results, they were elated to have discovered the telltale plutonium! But double-checking their results by replicating the analysis led to disappointment: their first sample had been contaminated by an experiment going on in a nearby lab—there was no plutonium in the sample at all, contradicting the supernova hypothesis (Fig. 10).

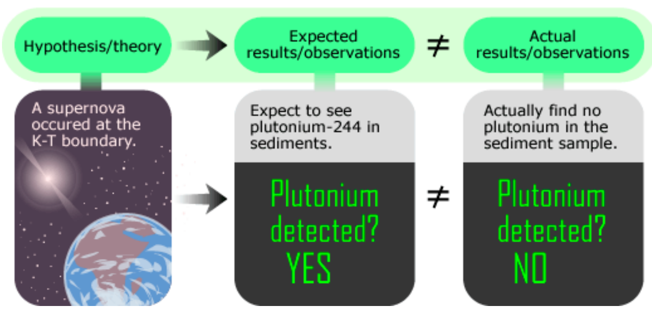
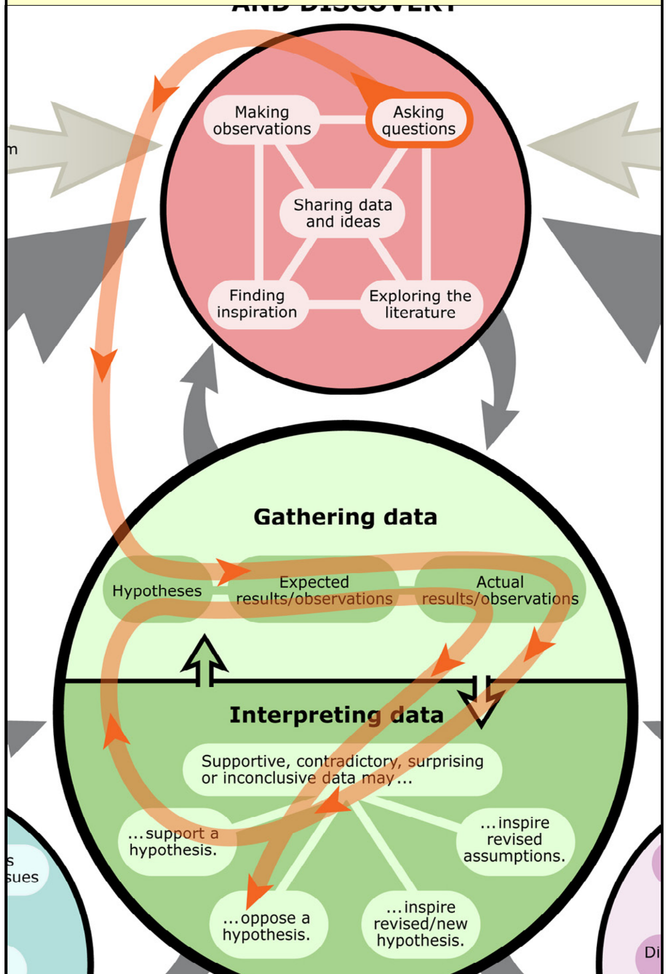


Fig. 10. Lack of plutonium contradicts the supernova hypothesis.

Walter's scientific journey so far:



Walter's iridium observation seemed to match up with an existing hypothesis about the dinosaur extinction but further investigation revealed observations that didn't fit the hypothesis.

Three observations, one hypothesis

The KT boundary layer contained plenty of iridium but no plutonium-244. Furthermore, the boundary marked what seemed to be a major extinction event for marine and terrestrial life, including the dinosaurs. What hypothesis would fit all those disparate observations and tie them together so that they made sense? The team came up with the idea of an asteroid impact—which would explain the iridium (since asteroids contain much more iridium than the Earth's crust) and the lack of plutonium—but which also led them to a new question: how could an asteroid impact have caused the dinosaur extinction (Fig. 11)?

Once again, Luis Alvarez came to the rescue with some calculations and an elaborated hypothesis. Talks with his colleagues led him to focus on the dust that would have been thrown into the atmosphere by a huge asteroid impact. He hypothesized that a huge asteroid had struck Earth at the end of the Cretaceous and had blown millions of tons of dust into the atmosphere. According to his calculations, this amount of dust would have blotted out the sun around the world, stopping photosynthesis and plant growth and hence, causing the global collapse of food webs (Fig. 12). This elaborated version of the hypothesis did indeed seem to fit with all three of the lines of evidence available so far: lack of plutonium, high iridium levels, and a major extinction event.

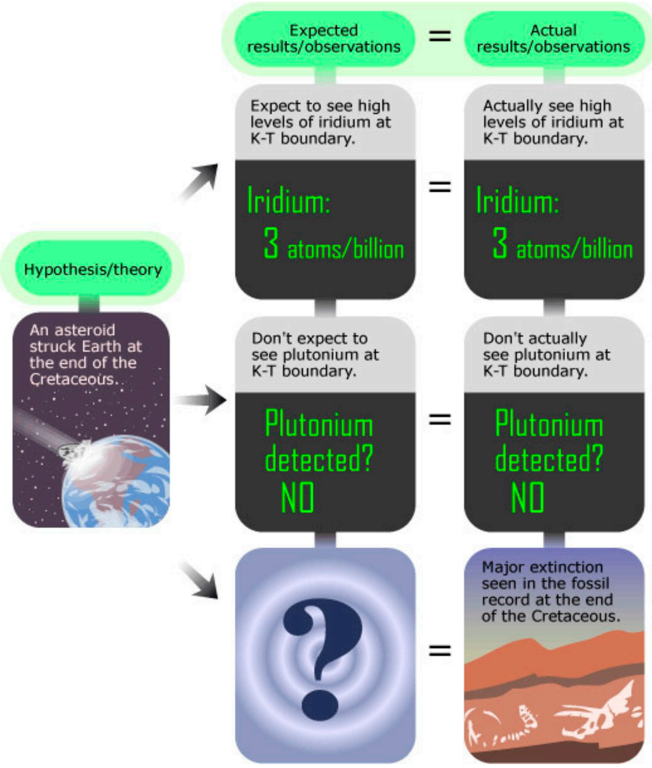


Fig. 11. The asteroid hypothesis fits iridium and plutonium observations—but how could it have caused a mass extinction?

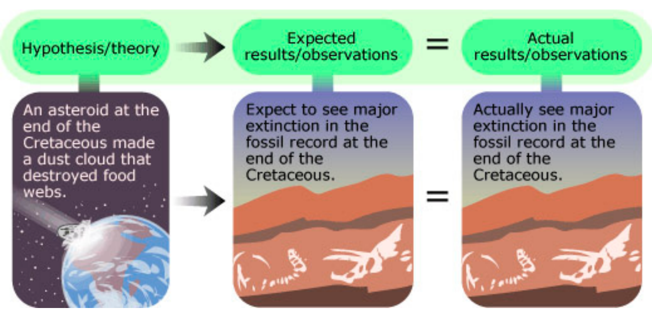
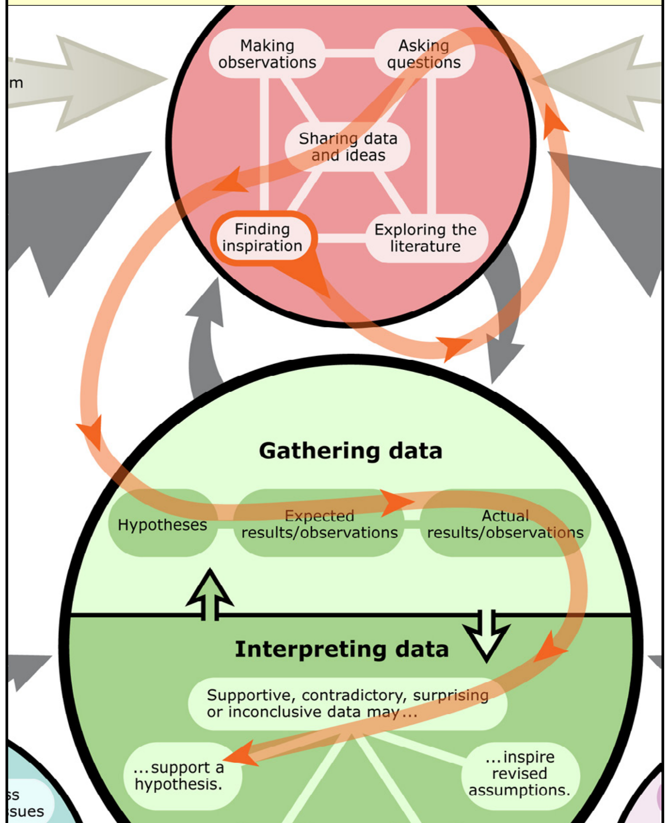


Fig. 12. The observation of a mass extinction makes sense, if the asteroid produced a dust cloud that blotted out the sun.

Walter's scientific journey so far:



The team comes up with a hypothesis that fits their iridium and plutonium observations, but wonders how their hypothesis might be related to the dinosaur extinction. Discussions with colleagues lead to an elaborated version of the hypothesis that fits with all three lines of evidence.

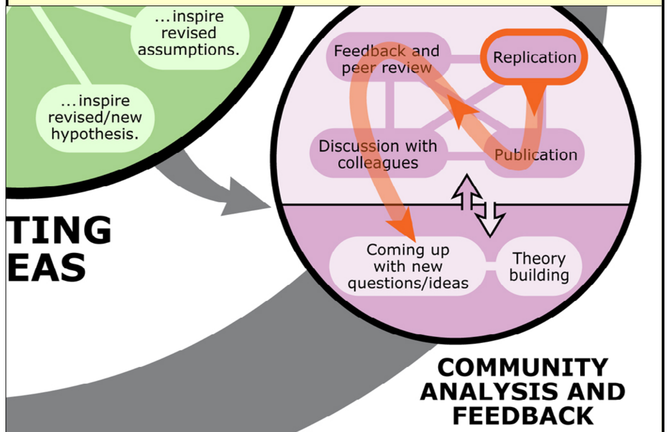
A storm front

Meanwhile, word of the iridium spike at the KT boundary in Italy and Denmark had spread. Scientists around the world had begun to try to replicate this discovery at other KT localities and had succeeded: many independent scientific teams confirmed that whatever event had led to the iridium anomaly had been global in scale (Fig. 13).

In 1980, amidst this excitement, Alvarez's team published their hypothesis linking the iridium anomaly and the dinosaur extinction in the journal *Science* and ignited a firestorm of debate and exploration. In the next ten years, more than 2000 scientific papers would be published on the topic. Scientists in the fields of paleontology, geology, chemistry, astronomy, and physics joined the fray, bringing new evidence and new ideas to the table.

Fig. 13. This world map shows some of the sites where an iridium anomaly at the KT boundary has been observed.

Walter's scientific journey so far:



As their results are replicated by others, the team publishes their hypothesis—and inspires a vigorous debate within the scientific community.

The eye of the storm

A real scientific controversy had begun. Scientists were confident that dinosaurs had gone extinct and were confident that a widespread iridium anomaly marked the KT boundary; however, they vehemently debated the relationship between the two and the cause of the iridium anomaly.

Alvarez's team hypothesized a specific cause for a one-time historical event that no one was around to directly observe. You might think that this would make the hypothesis impossible to test or that relevant evidence would be hard to come by. Far from it. In fact, the scientific community picked up the idea and ran with it, exploring many other lines of evidence, all relevant to the asteroid hypothesis.

Extinctions: If an asteroid impact had actually caused a global ecological disaster, it would have led to the sudden extinction of many different groups. Thus, if the asteroid hypothesis were correct, we would expect to find many extinctions in the fossil record that line up exactly with the KT boundary, and fewer that occurred in the millions of years leading up to the end of the Cretaceous (Fig. 14).

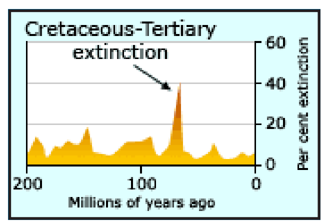


Fig. 14. Percentage of organisms that have gone extinct over the past 200 million years, based on the fossil record.

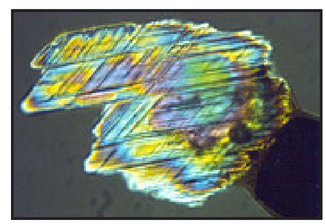


Fig. 15. The two sets of planar lamellae in this quartz grain from the KT boundary in the Raton Basin, Colorado, are strong evidence of an impact origin.

Impact debris: If a huge asteroid had struck Earth at the end of the Cretaceous, it would have flung off particles from the impact site. Thus, if the asteroid hypothesis were correct, we would expect to find particles from the impact site in the KT boundary layer.

Glass: If a huge asteroid had struck Earth at the end of the Cretaceous, it would have generated a lot of heat, melting rock into glass, and flinging glass particles away from the impact site. Thus, if the asteroid hypothesis were correct, we would expect to find glass from the impact at the KT boundary.

Shockwaves: If a huge asteroid had struck Earth at the end of the Cretaceous, it would have generated powerful shockwaves. Thus, if the asteroid hypothesis is correct, we would expect to find evidence of these shockwaves (like telltale grains of quartz with deformations caused by the shock; Fig. 15) at the KT boundary.

Shocked quartz grain from U.S. Geological Survey/photo by G.A. Izett

Fig. 16. These tsunami-derived ridges of rubble along the southeastern coastline of Bonaire are not from the KT, but suggest the sort of tsunami debris we should expect to identify near the KT boundary.

Fig. 17. Meteor Crater in Arizona does not date to the KT, but suggests the sort of landform that a massive asteroid would leave behind.

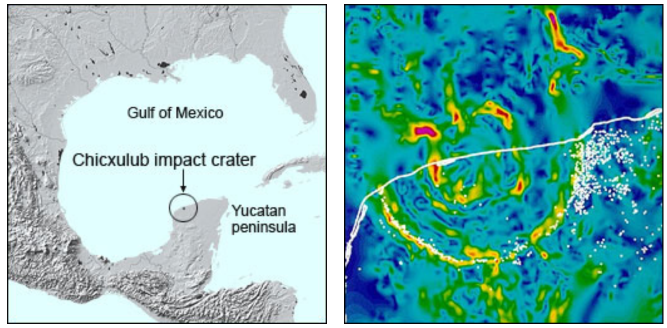


Fig. 18. At left, a map showing the location of the Chicxulub impact crater. At right, a horizontal gradient map of the gravity anomaly over the Chicxulub crater, constructed from data collected by Mexico during oil exploration and augmented by additional data from various universities and the Geological Survey of Canada. The white line indicates the Yucatan coastline. The white dots represent the locations of sinkholes (cenotes).

Tsunami debris: If a huge asteroid had struck one of Earth's oceans at the end of the Cretaceous, it would have caused tsunamis, which would have scraped up sediments from the bottom of the ocean and deposited them elsewhere (Fig. 16). Thus, if the asteroid hypothesis were correct, we would expect to find debris beds from tsunamis at the KT boundary.

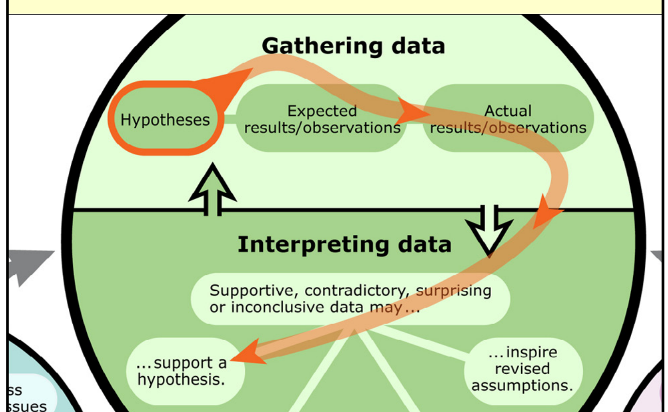
Crater: If a huge asteroid had struck Earth at the end of the Cretaceous, it would have left behind a huge crater (Fig. 17). Thus, if the asteroid hypothesis were correct (and assuming that the crater was not subsequently destroyed by tectonic action), we would expect to find a gigantic crater somewhere on Earth dating to the end of the Cretaceous.

The evidence relevant to each of these expectations is complex (each is a lesson in the nature of science on its own!) and involved the work of scientists all around the world. The upshot of all that work, discussion, and scrutiny was that most lines of evidence seemed to be consistent with the asteroid hypothesis. The KT boundary is marked by impact debris, bits of glass, shocked quartz, tsunami debris—and of course, the crater.

The hundred-mile-wide Chicxulub crater is buried off the Yucatan Peninsula (Fig. 18). Shortly after Alvarez's team published their asteroid hypothesis in 1980, a Mexican oil company had identified Chicxulub as the site of a massive asteroid impact. However, since the discovery was made in the context of oil exploration, it was not widely publicized in the scientific literature. It wasn't until 1991 that geologists connected the relevant observations (e.g., quirks in the pull of gravity near Chicxulub) with the asteroid hypothesis.

Chicxulub might seem to be "the smoking gun" of the dinosaur extinction (as it has sometimes been called)—but in fact, it is far from the last word on the asteroid hypothesis …

Walter's scientific journey so far:



Multiple lines of evidence are explored by many different members of the scientific community and, for the most part, seem to support the hypothesis.

Tsunami debris photo courtesy of Anja Scheffers, Southern Cross University; Meteor Crater photo from NASA/photo by D. Roddy; gravity anomaly map from A. HIldebrand, M. Pilkington, and M. Connors

It's not over 'til …

Scientific ideas are always open to question and to new lines of evidence, so although many observations are consistent with the asteroid hypothesis, the investigation continues. So far, the evidence supports the idea that a giant asteroid struck Earth at the end of the Cretaceous—but did it actually cause most of the extinctions at that time? Some observations point to additional explanations. Further research (much of it spurred by the asteroid hypothesis) has revealed the end of the Cretaceous to be a chaotic time on Earth, even ignoring the issue of a massive asteroid collision. Volcanic activity peaked, producing lava flows that now cover about 200,000 square miles of India; major climate change was underway with general cooling punctuated by at least one intense period of global warming; sea level dropped and continents shifted with tectonic movements. With all this change going on, ecosystems were surely disrupted. These factors could certainly have played a role in triggering the mass extinction—but did they?

In short, the evidence points to several potential culprits for the mass extinction (Fig. 19). Which is the true cause? Well, perhaps they all are.

Just as the extinction of an endangered species today may be traced to many contributing factors (global warming, habitat destruction, an invasive predator, etc.), the KT mass extinction may have been triggered by several different agents (e.g., volcanism and an asteroid impact, with a bit of climate change thrown into the mix). If this is indeed the case and multiple causes were in play, teasing them apart will require a more integrative approach, exploring the relationships between abiotic factors (like asteroid impacts and sea level change) and extinction: which groups survived the mass extinction and which did not? Birds, for example, survived the extinction, but all other dinosaurs went extinct. What does this tell us about the cause of the extinction? Are there different patterns of extinction in different ecosystems or different parts of the world? Do these differences point to separate causal mechanisms?

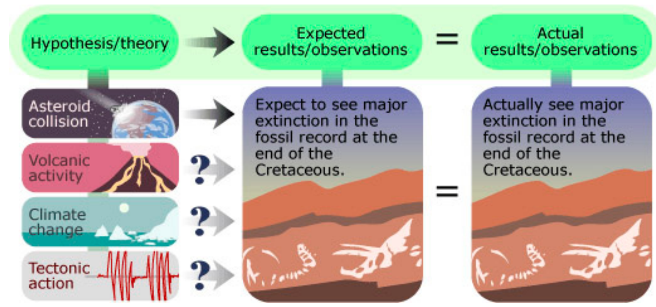
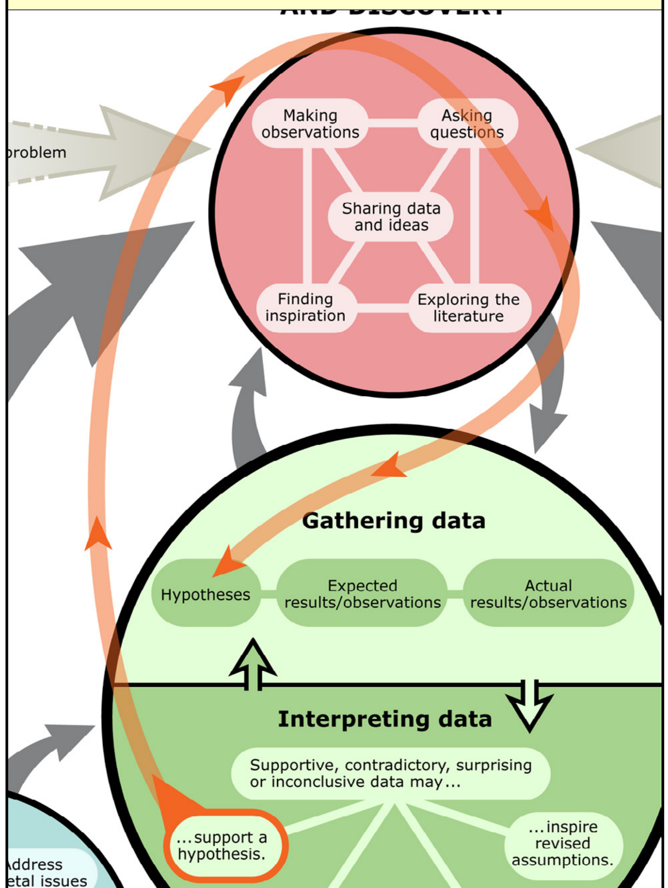


Fig. 19. Many factors might have contributed to the KT extinction.

Walter's scientific journey so far:



Evidence strongly supports part of the hypothesis, but leads to even more questions and hypotheses.

More knowledge, more questions

At first glance, this snapshot of science might seem to have backtracked. First, the story is full of false starts and abandoned goals: Alvarez's work on plate tectonics was sidetracked by his intriguing observations of the KT boundary. Then his work on the timing of the KT transition was sidetracked by the iridium intrigue. The supernova hypothesis was abandoned when critical evidence failed to materialize. And now, scientists are wondering if the asteroid hypothesis can really explain the whole mass extinction. Our questions regarding the KT extinction have multiplied since this investigation began.

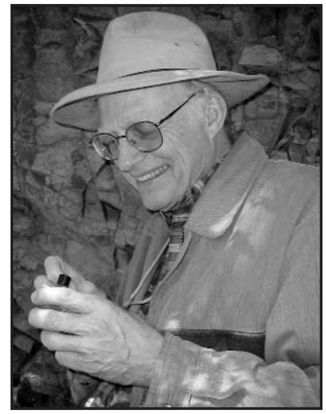


Fig. 20. Walter Alvarez in 2002.

All that is true; however, we also have more knowledge about events at the end of the Cretaceous than we did before Walter Alvarez (Fig. 20) began poking around in the Apennines. We know that a massive asteroid struck Earth, probably near the Yucatan Peninsula. We know that no nearby supernova rained plutonium down on Earth. We know more about the fossil record surrounding the KT. We have a more detailed understanding of the climatic and geologic changes leading up to the end of the Cretaceous. In a sense, we have so many more questions simply because we know so much more about what to ask, and this is a fundamental part of the scientific enterprise. Science is both cumulative and continuing. Each question that we answer adds to our overall understanding of the natural world, but the light that is shed by that new knowledge highlights many more areas still in shadow.

Want to learn more? Check out these references

Popular and historical accounts:

Alvarez, W. 1997. *T. rex* and the crater of doom. Princeton, NJ: Princeton University Press.

Rogers, P.W. 1979. LBL News Magazine. Available at http://www.lbl.gov/Science-Articles/Archive/dino-saur-extinction.html

A few scientific articles:

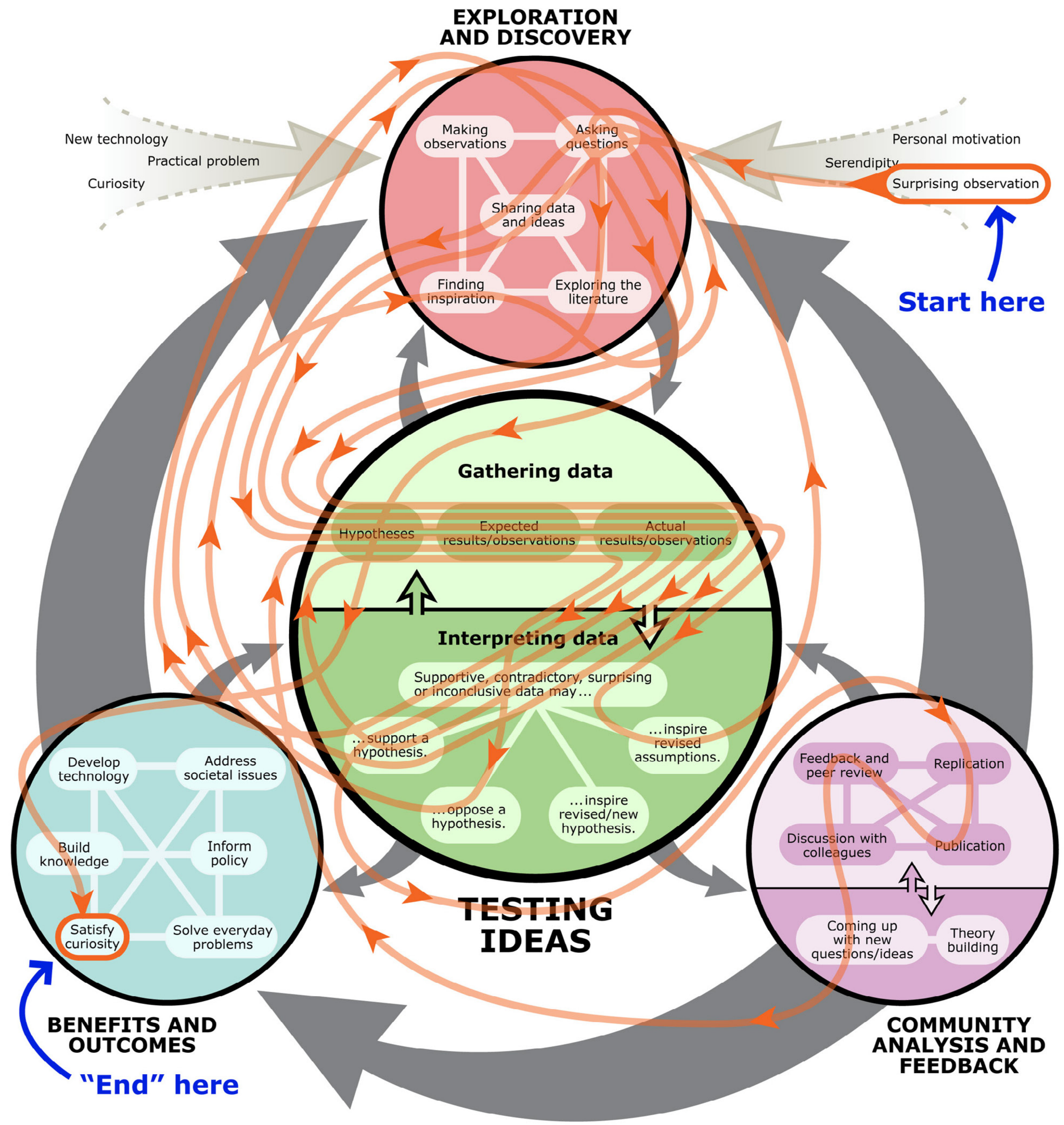
Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208:1095–1108.

Hildebrand, A.R., G.T. Penfield, D.A. Kring, M. Pilkington, Z.A. Camargo, S.B. Jacobson, and W.V. Boynton. 1991. Chicxulub crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatan Peninsula, Mexico. *Geology* 19:867–871.

Russell, D.A., and W. Tucker. 1971. Supernovae and the extinction of the dinosaurs. *Nature* 229:553–554.

Walter Alvarez photo courtesy of the Geological Society of America

Review the scientific journey taken by Walter and his colleagues:



Key points:
- The process of science is non-linear, unpredictable, and ongoing.
- Testing ideas is at the core of science.
- Many hypotheses may be explored in a single investigation.
- A single hypothesis may be tested many times against many lines of evidence.