The Impact and Volcanism Theories of Extinction and Change at the Cretaceous-Tertiary Boundary: Constraining Evidence

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***Writer's comment:** The following is my term paper for Geology 113G, "The Solar System." I am not a science major and I approach science papers with some trepidation—the writing style allows for much less interpretation than I am used to. What helped me overcome this unfamiliarity and draw me into the paper was my interest in the topic I picked. Because I was somewhat acquainted with the problems surrounding the extinction of the dinosaurs (the most widely known event occurring at the Cretaceous-Tertiary boundary), this paper was an opportunity for me learn more about the very complex debate taking place within scientific circles as to just what really happened at the Cretaceous-Tertiary (K/T) boundary.*

Basically, this paper is an attempt to compare and contrast the two most widely-accepted theories regarding the cause of the extinctions that occurred at the K/T boundary. I tried to keep my use of scientific terminology to a minimum, but the "jargon" associated with this or any field serves a purpose—to communicate a complex, specialized, or just plain lengthy concept to the reader using a minimum of space while retaining maximum clarity. For example, it's easier (and shorter) to write "m.y. B.P." than it is to write "million years before the present." Of course, if a reader is unfamiliar with the terminology, the ideas the writer is trying to communicate may be lost. I think, however, that most of the terminology I used in this paper is pretty easy to understand just from the context it's used in.

Regardless of whether or not this paper makes interesting reading, I hope it will help those who find themselves faced with the prospect of writing a paper in an unfamiliar area—it can be done!

-John Ferrari

***Instructor's comment:** The final essay for "The Solar System" is intended to demonstrate a synthesis of several ideas explored in Geology 113 and a grasp of the facts pertinent to the topic at hand. John Ferrari's succinct, interesting and informative essay goes beyond this. His depth of understanding and attention to detail approaches that found in professional publications. I do not mean to say that the essay is perfect: there are several scientific lapses. What is more important is that the essay was written in John's own words and is not a parroting of the articles he cited. It is clear that John has internalized the ideas present in the many papers he researched. Above all, his conclusions show independent thinking and critical evaluation of two currently debated scientific theories—whether copious volcanism or a collision between the Earth and a hugh meteor caused the demise of the dinosaurs.*

-Anne Hofmeister, Assistant Professor, Geology

Introduction

In the ten years since Luis and Walter Alvarez (1980) first published their theory of an extraterrestrial causation for the events associated with the Cretaceous-Tertiary boundary, a tremendous amount of research focusing on geological and paleontological analyses of the K/T boundary layer has been conducted. While this research has yielded a vast body of data and information focused upon a single subject area (the K/T boundary), a widely-accepted synthesis of the data has yet to be formulated

Two major hypotheses have been developed in an attempt to explain the biological and geological K/T boundary events. The first of these hypotheses is the impact theory proposed by Luis and Walter Alvarez (1980). This theory suggests that an asteroid or comet with a diameter of ~10 km (Alvarez, 1987) collided with the Earth 65 m.y. B.P., at the time of the K/T boundary (Alvarez *et al.*, 1980; Alvarez, 1987). The impact of this object would have created a crater approximately 150 to 200 km in diameter (Hallam, 1987), releasing energy equivalent to 10^8 megatons of TNT and creating a supersonic plume of ejecta (Alvarez, 1987). According to recent models, the shock atmospheric heating caused by the injection of a plume of superheated ejecta material into the atmosphere would produce nitrogen oxides, leading to acid rain persisting for up to a year (Chapman, 1989). Impact ejecta material, remaining airborne in the stratosphere for months, would create a primeval "nuclear winter." According to the impact theory, the combined effects of these catastrophic events account for the extinctions associated with the K/T boundary.

The second hypothesis rejects any extraterrestrial influence as the primary cause of the K/T boundary events in favor of a terrestrial causation. This volcanism theory posits a period of intense flood basalt volcanism which formed the massive Deccan Traps in India (White, 1989) coupled with substantial explosive volcanism in an extensive region from the South Atlantic to the Antarctic (Hallam, 1987). The volcanism theory proposes that this volcanic activity culminated at the K/T boundary 65 m.y. B.P. and was the primary cause of the K/T boundary extinctions. Proponents of this theory point out that flood basalt fissure eruptions such as the ones that created the Deccan Traps are capable of injecting substantial quantities of sulfate aerosols into the lower stratosphere, leading to the production of acid rain, ozone layer depletion, and global atmospheric cooling, reinforced by ash expelled into the atmosphere (Hallam, 1987).

In this paper I will detail two of the most important geologic constraints affecting both the impact and volcanism theories—the presence of a sharp iridium spike in the K/T boundary clay layer and the existence of shocked minerals found at many K/T boundary sites. Table 1 is a summary of the compatibility of this evidence with the two theories.

Iridium and Rare Siderophile Enrichment at the K/T Boundary

The presence of anomalously high concentrations of iridium in the K/T boundary layer remains one of the primary pieces of evidence used to support the impact theory. Terrestrial iridium concentrations are often measured in parts per trillion; the abundance of iridium in the crust of the Earth is extremely small. However, the iridium concentration in the K/T boundary clay layer at Gubbio, Italy (the site which stimulated the original formulation of the impact theory), rises rapidly by a factor of 300 at the bottom of the clay layer, after which it falls back slowly to the background level (Alvarez, 1987).

Anomalous iridium contents of the same magnitude as that documented at the Gubbio site have now been identified at over 75 K/T boundary clay layer sites worldwide by eleven different laboratories (Alvarez, 1986). Certainly this is not consistent with normal terrestrial iridium values. However, meteorites often exhibit iridium abundances over ten thousand times normal terrestrial iridium abundances; it was this fact that led to the original proposal of an asteroid impact (Alvarez, 1987). A total deposition of approximately 0.5 million tons of iridium was estimated to have resulted from the hypothesized impact (Alvarez, 1987); this estimate was arrived at by adding up the amount of iridium in the K/T boundary layer clay on each square centimeter of the Earth. Assuming a base iridium abundance of 0.5 parts per million, common in certain primitive meteorites and representative of Solar System debris, a diameter of ~10 km was calculated for the impacting bolide (Alvarez, 1987). If the iridium spike found worldwide in the K/T boundary clay layer is the result of a massive bolide impact, other rare siderophile (or "cosmic-occurring") elements, such as platinum and osmium, and related elements, such as gold, should also be present in the clay layer in amounts consistent with abundances found in meteorites. The ratios of these elements in the K/T boundary clay layer at a site in Denmark generally match the ratios of the chondritic or cosmic pattern (Ganapathy, 1980), a fact which was subsequently confirmed at other K/T boundary sites (Alvarez, 1986).

Proponents of the volcanism theory reject the notion that the iridium spike observed in the K/T boundary clay layer requires a bolide impact. They propose instead that the iridium spike was caused by intense volcanic activity with a deep mantle source of magma (Alvarez, 1986). The report of an aerosol eruption at Kilauea, Hawaii, containing an enormous enrichment of iridium 10^5 times the normal iridium abundances measured in Kilauean lava flows, apparently due to the derivation of the magma from the deep mantle, proved the feasibility of this hypothesis (Hallam, 1987). Further evidence supporting the volcanism explanation of the K/T iridium spike is found in the fact that the mass of iridium in the K/T boundary clay layer worldwide is roughly equivalent to the iridium that should have been released during the activity of the Deccan Traps volcanism in India (Olmez *et al.*, 1986). Evidence against the impact theory includes an osmium ratio at a K/T site in Denmark that is significantly higher than the osmium ratios typical of meteorites but which corresponds closely to the osmium ratio of the mantle-derived Bushveld Complex of South Africa (Hallam, 1987). The isotopic compositions of noble gases at the Denmark site are identical to those of the Earth's atmosphere and do not record contamination by meteoric material (Hallam, 1987).

All estimations of iridium concentrations within the K/T boundary clay layer depend upon the estimated deposition time of the clay layer. While the volcanism theory holds that the K/T boundary clay layer was deposited over a long period of time, the impact theory presupposes that the clay layer represents no more than a year (Alvarez, 1986). Obviously, if the clay layer was, in fact, deposited over a long period of time, the argument supporting the volcanism theory is greatly enhanced. This is particularly true as estimates for the duration of the Deccan Traps volcanism suppose the bulk of the volcanism to have occurred in three main intervals each lasting perhaps only 50,000 to 100,000 years (Courtillot, 1988), a reasonable time frame for the deposition of the K/T boundary clay layer. If, on the other hand, the K/T boundary clay layer was deposited in only a year, the volcanism theory's explanation for the presence of the iridium spike suffers a loss of credibility.

The Presence of Shocked Minerals at the K/T Boundary

Impressive evidence in favor of the impact theory is found in the existence of shocked minerals distributed worldwide at the K/T boundary. The mineral which has been most observed is shocked quartz displaying multiple laminar features generally held to be uniquely characteristic of impact deformation (Hallam, 1987). The creation of shock lamellae seem to require the passage of a shock wave through the host rock body (Alvarez, 1986); such a shock wave would have been produced by an impacting event, but it has not yet been proven that volcanic activity can produce such a shock wave. The shocked quartz found in the K/T boundary clay layer is of silt to sand size and has been located at terrestrial K/T boundary sites in the western United States and at marine K/T boundary sites in Europe and Soviet Turkmenia. The global distribution of this shocked quartz is probably the result of dispersal outside the atmosphere (Alvarez, 1986). While the ejection of silt- to sand-sized particles into the upper boundaries of the atmosphere is a plausible result of a large impacting event, only incredibly violent volcanism could account for such ejection—it certainly could not result from the quiet flood basalt volcanism that formed the Deccan Traps. The case for impact was strengthened with the discovery of stishovite at the K/T boundary (Chapman, 1989)—the creation of this high-pressure silicate requires even higher pressures than does shocked quartz, providing further evidence against the volcanism theory. The apparent absence of stishovite had been used by some proponents of the volcanism theory as detracting from the impact theory (Chapman, 1989).

Pro-volcanists defend the volcanism theory in this area by pointing out that shock mosaicism has been documented in plagioclase and biotite phenocrysts from the Toba caldera in Sumatra (Hallam, 1987), demonstrating that volcanism can produce shock features. While multiple laminar features are not likely to occur in volcanic minerals due to annealing at high temperatures, they might occur in country rock surrounding sites of highly explosive volcanism (Hallam, 1987). This leads to the question of whether explosive volcanism can generate pressures sufficient (a minimum of 90 kbar) to create shocked quartz; modeling based on the Mt. St. Helens' eruption seems to indicate that this is possible (Hallam, 1987). So far, volcanism proponents have been unable to formulate a credible hypothesis to account for the worldwide distribution of the shocked minerals.

Summary and Conclusion

The past decade has seen a wealth of research conducted in the area of possible mechanisms for the extinctions associated with the Cretaceous-Tertiary boundary layer, the interest in this field having been sparked originally by the novel impact theory first proposed by Luis and Walter Alvarez (1980). Since the initial proposal of this impact theory, which attributes the K/T boundary events to the impact of a bolide some 10 km in diameter (Alvarez *et al.*, 1980; Alvarez, 1987), a strong opposition theory has been formulated. The advocates of this volcanism theory propose that a period of intense volcanism, culminating at the time of the K/T boundary, was the primary cause of the K/T boundary events (White, 1989). While many pieces of evidence have been used to support—or discredit—either of the two theories, two of the most important pieces of geologic evidence are the presence of an anomalous iridium spike found within the K/T boundary clay layer and shocked minerals, principally shocked quartz and stishovite, associated with the K/T boundary layer.

Both of these pieces of evidence can be explained by the impact theory. Meteorites often contain abundances of iridium sufficient to account for the observed iridium enrichment in the K/T boundary layer, and the impact of a ~10 km bolide would be sufficient both to create shocked quartz with multiple lamellae features and stishovite, and, through ejection of material into the stratosphere or space, to distribute these minerals globally (Alvarez, 1986).

The volcanism theory offers plausible evidence to account for the iridium spike in the discovery of large concentrations of iridium present in a Kilauean aerosol (Hallam, 1987). It has also been estimated that the amount of iridium present in the K/T boundary clay layer roughly matches the amount of iridium that should have been released during the period of the Indian Deccan Traps volcanism (Olmez *et al.*, 1986), which was contemporaneous with the K/T boundary. However, evidence used by pro-volcanists to account for the creation of shocked minerals, such as those observed at the K/T boundary layer, remains minimal. In this area proponents of the volcanism theory rely for the most part on theoretical modelling to support their views (Hallam, 1987).

While no consensus has yet been reached regarding which of the two theories is correct, as more data become available either the impact theory or the volcanism theory should be strengthened through sheer weight of supporting evidence. In particular, the influence of paleontological evidence—as opposed to geologic evidence of the type presented in this paper—will contribute to the constraints affecting both the impact and volcanism theories by providing detailed information on the time span involved for the K/T boundary extinctions. While the impact theory implicitly assumes a single catastrophic event (the impacting event) which led to the quick initiation and completion of the K/T boundary extinction events, the volcanism theory is more flexible in the range of extinction time frames compatible with the theory. Indeed, paleontological evidence suggesting an extended period of slow extinction which began before the deposition of the K/T boundary clay layer may prove to be a major basis of support for the volcanism theory.

Also, the idea that the impact and volcanism theories may each independently explain the K/T boundary events has been increasingly assailed. While no evidence that automatically refutes either the impact theory or the volcanism theory has yet been discovered, the existing evidence seems to indicate that the actual mechanism(s) responsible for the K/T boundary extinctions and the geologic anomalies associated with the K/T boundary layer cannot be explained by either of the two theories individually. The true causation of the K/T boundary events may well encompass both the impact and volcanism theories. One modification of the impact theory, for example, posits the impact of several bolides which in turn triggered the massive volcanic eruptions proposed by the volcanism theory (White, 1989). The question of causation mechanisms for the events associated with the K/T boundary is far from closed.

TABLE 1. Compatability of Observational Evidence from the Cretaceous-Tertiary Boundary With Impact of Volcanism as the Causal Mechanism

Observational Evidence	**Impact Event**	**Volcanic Eruption**	
		Quiet Basaltic	Violent Siliceous
Iridium	**Yes:** all types of meteorites have high iridium	**Possibly:** high iridium content found in Kilauea gas	**No:** high iridium not yet found in any silicic ejecta
Shocked Minerals	**Yes:** shocked quartz and stishovite found at sites	**No:** large explosions do not occur in this setting	**Possibly:** based on modelling only

Adapted from Alvarez, 1986.

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