Most mass extinctions over the past 500 million years in Earth's history occurred during times of major volcanic eruptions; some occurred at times of multiple impacts (Fig. 1), and all were accompanied by major changes in climate, sea level, and oxygenation levels of the water column (Hallam and Wignall, 1997; Courtillot et al., 2000; Wignall, 2001; Courtillot and Renne, 2003; Keller, 2005, 2008a). But among the five major mass extinctions, only the Cretaceous–Tertiary boundary (KTB) mass extinction can be shown to have a close correspondence between an iridium anomaly that is commonly assumed to represent an impact, an impact crater (Chicxulub), a large igneous province (Deccan Traps), and major changes in climate and sea level (Fig. 2).

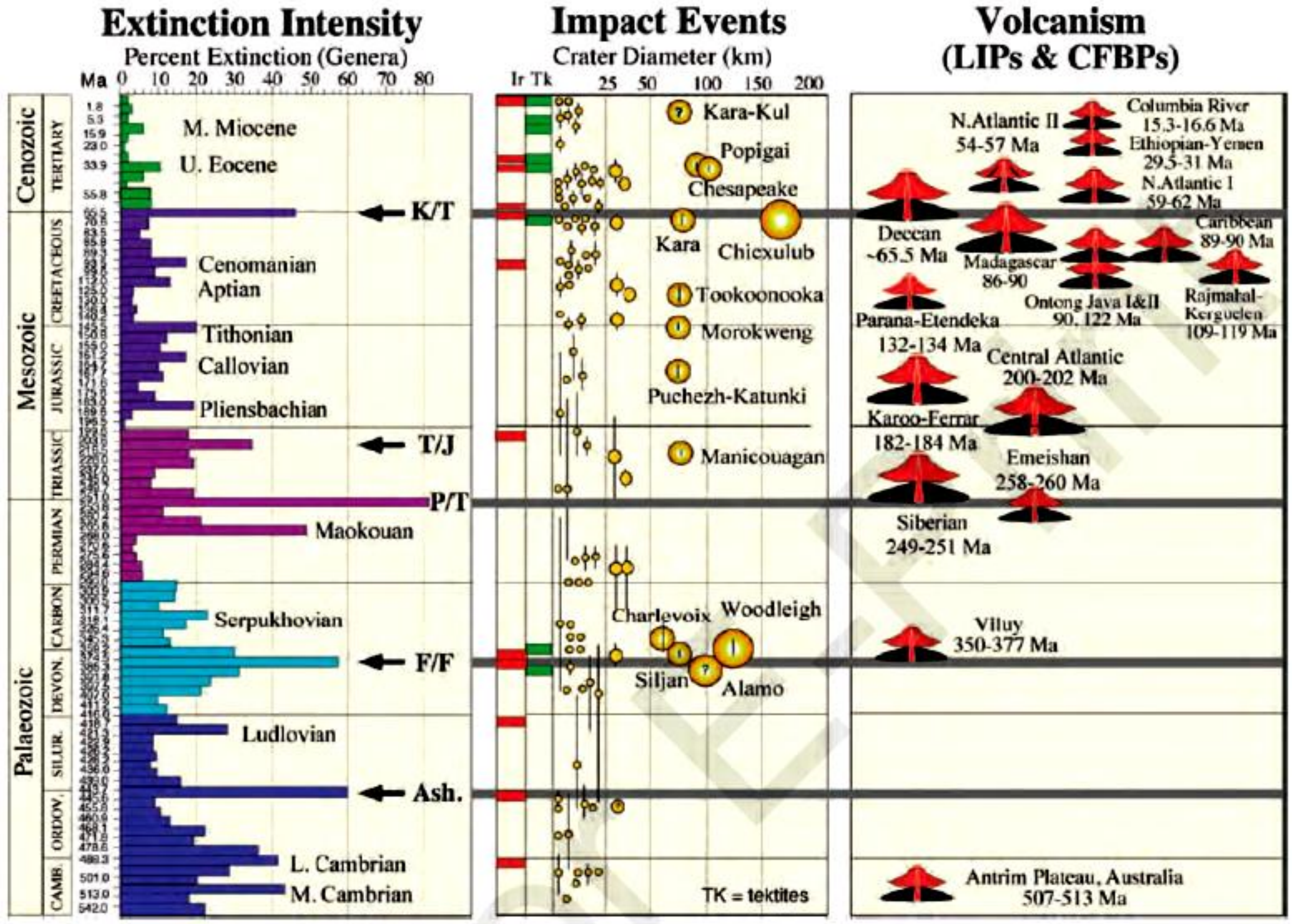


FIGURE 1.—Mass extinctions, impacts, and large igneous provinces during the Phanerozoic. Note that the **Chicxulub impact predates the KT boundary by 300 ky.**

The boundary marks the end of the Mesozoic Era, and the beginning of the Cenozoic Era,The KTB mass extinction differs from the other four major mass extinctions in that it occurred after the longest period (145–65.5 Ma) with the lowest background extinctions (, 10%). Throughout the Cretaceous, generic diversity steadily increased due to major increase in nutrients as a result of long-term climate change and possibly volcanic activity.

## Possible causes

The cause(s) for the end-Cretaceous mass extinction following this long period of globally increasing diversity must be related to the twin catastrophes of Deccan volcanism and a large meteorite impact.

1. **IMPACT-KILL HYPOTHESIS:** In 1980, Nobel prize-winning physicist Luis Alvarez and team discovered iridium anomaly at the KT boundary (sedimentary layers) at Gubio, Italy and also found all over the world with a concentration of iridium many times greater than normal (30 times and 130 times the background). Iridium is extremely rare in the earth's crust because it is a siderophile, and therefore most of it travelled with the iron as it sank into the earth's core during planetary differentiation. As iridium remains abundant in most asteroids and comets, the Alvarez team suggested that an asteroid struck the earth at the time of the K–T boundary. The evidence for the Alvarez impact theory is supported by chondritic meteorites and asteroids which have an iridium concentration of ~455 parts per billion, much higher than ~0.3 parts per billion typical of the earth's crust. Shocked quartz granules and tektite glass spherules, indicative of an impact event, are also common in the K–T boundary, especially in deposits from around the Caribbean. All of these constituents are embedded in a layer of clay, which the Alvarez team interpreted as the debris spread all over the world by the impact.

   The Alvarez team calculated the size of the asteroid to be about 10 kilometers (6 mi) in diameter. Such a large impact would have had approximately the energy of 100 trillion tons of TNT, or about 2 million times greater than the most powerful thermonuclear bomb ever tested.

   The obvious consequence of an impact would be a dust cloud which would block sunlight and inhibit photosynthesis for a few years. This would account for the extinction of plants and phytoplankton and of organisms dependent on them (including predatory animals as well as herbivores). However, small creatures whose food chains were based on detritus might have still had a reasonable chance of survival. It is estimated that sulfuric acid aerosols were injected into the stratosphere, leading to a 10–20% reduction in sunlight reaching the earth's surface. It would have taken at least ten years for those aerosols to dissipate. Global firestorms may have resulted as incendiary fragments from the blast fell back to Earth. Analyses of fluid inclusions in ancient amber suggest that the oxygen content of the atmosphere was very high (30–35%) during the late Cretaceous. This high $O_2$ level would have supported intense combustion. The level of atmospheric $O_2$ plummeted in the early Tertiary Period. If widespread fires occurred, they would have increased the $CO_2$ content of the atmosphere and caused a temporary greenhouse effect once the dust cloud settled, and this would have exterminated the most vulnerable survivors of the "long winter". Impact theories can only explain very rapid extinctions, since the dust clouds and possible sulphuric aerosols would wash out of the atmosphere in a fairly short time—possibly under ten years.

   **Chicxulub Crater**

   Subsequent research in 1990 identified the Chicxulub Crater buried under Chicxulub on the coast of Yucatan, Mexico as the impact crater which matched the Alvarez hypothesis. The crater is oval, with an average diameter of about 180 kilometers (112 mi).

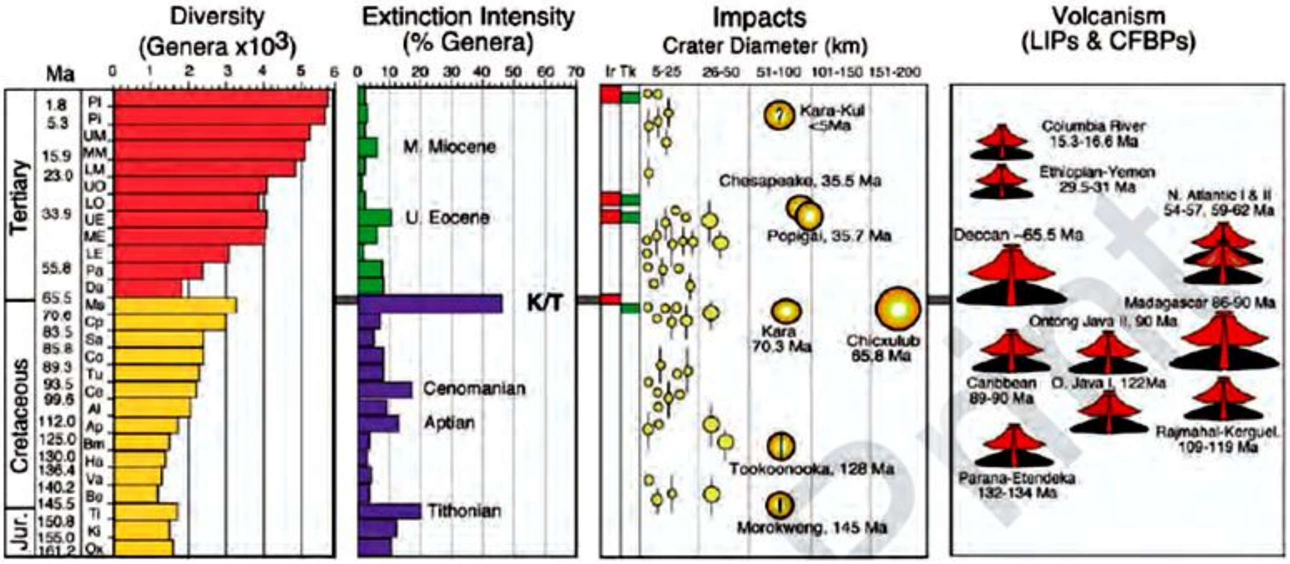


FIGURE 2.—Diversity and extinction intensity correlated with the impact crater record and large igneous provinces during the Cretaceous and Cenozoic. Note that the Chicxulub impact predates the KT boundary by about 300 ky (Keller et al., 2003a; Keller et al., 2004a; Keller et al., 2004b; Keller et al., 2007). The main phase (80%) of the Deccan volcanic province occurred at the end of the Maastrichtian (Chenet et al., 2007; Chenet et al., 2009) and ended at the KT mass extinction (Keller et al., 2008a).

The asteroid landed right on the coast and would have caused gigantic tsunamis, for which evidence has been found all round the coast of the Caribbean and eastern United States—marine sand in locations which were then inland, and vegetation debris and terrestrial rocks in marine sediments dated to the time of the impact. The asteroid landed in a bed of gypsum (calcium sulphate), which would have produced a vast sulphur dioxide aerosol. This would have further reduced the sunlight reaching the earth's surface and then precipitated as acid rain, killing vegetation, plankton and organisms which build shells from calcium carbonate (coccolithophorids and molluscs). The crater's shape suggests that the asteroid landed at an angle of 20° to 30° from horizontal and traveling north-west. This would have directed most of the blast and solid debris into the central part of what is now the United States.

Gerta Keller suggests that the Chicxulub impact occurred approximately 300,000 years before the K–T boundary. This dating is based on evidence collected in Northeast Mexico, detailing multiple stratigraphic layers containing impact spherules, the earliest of which occurs approximately 10 meters (33 ft) below the K–T boundary.


**Age of Chicxulub Impact:** The oldest spherule layer predates the KT boundary by as much as 300,000 years as determined from its position near the base of planktic foraminiferal zone, which spans the last 300,000 years of the Maastrichtian.

## 2. Deccan Traps:

Chenet et al. (2007), Chenet et al. (2008), and Chenet et al. (2009) estimated that the bulk (80%) of the 3500-m-thick Deccan traps was deposited over a very short time period—possibly less than 10,000 years, with most of this time represented by periods of quiescence between volcanic eruptions (e.g., intertrappean sedimentation). The entire Deccan lava pile erupted in three phases, with the first and smallest phase at 67.4 My, the main phase at or near the KTB, and the last smaller phase at the C29r–C29n transition in the early Danian. Keller et al. (2008a) discovered that the KTB mass extinction coincided with the end of the main phase of Deccan volcanism. Rajahmundry area of the Krishna–Godavari Basin of southeastern India --in this area Deccan eruptions, known as the Rajahmundry traps, mark the end of the main phase of Deccan volcanism and the world's longest lava flows, extending over 1500 km across the Indian continent and into the Bay of Bengal. Sediments immediately below mark the mass extinction in planktic foraminifera.

Deccan Traps flood basalts caused the extinction were usually linked to the view that the extinction was gradual, as the flood basalt events were thought to have started around 68 mya and lasted for over 2 million years. However, there is evidence that two-thirds of the Deccan Traps were created in 1 million years about 65.5 mya, so these eruptions would have caused a fairly rapid extinction, possibly a period of thousands of years, but still a longer period than what would be expected from a single impact event. The Deccan Traps could have caused extinction through several mechanisms, including the release of dust and sulphuric aerosols into the air which might have blocked sunlight and thereby reducing photosynthesis in plants. In addition, Deccan Trap volcanism might have resulted in carbon dioxide emissions which would have increased the greenhouse effect when the dust and aerosols cleared from the atmosphere.

## Biological impacts

The non-avian dinosaur families that went extinct 65 million years ago include:
tyrannosaurids, ornithomimids, dromaeosaurids, titanosaurid sauropods, nodosaurids, ankylosaurids, hypsilophodontids, hadrosaurids, pachycephalosaurids, protoceratopsids, and ceratopsids. Land plants: fossils consist of palynoflora (spores and pollen) and megafossils (leaves, wood). The K/T is characterized by an abrupt increase in the percentage of fern spores (representing the 'pioneer', 'recovery' or invasive community that recolonized the continents following the extinction event). Plant megafossils suggest an abrupt decline in diversity ('deforestation') at the extinction boundary. Land animals (see below): organisms that lived in freshwater had a survivorship rate of up to 90%; animals that live completely on land had a survivorship rate of as little 10%. Aquatic animals such as fish, turtles, crocs and amphibians were not profoundly affected. Size and metabolism were also factors: small animals survived preferentially and ectotherms survived preferentially (if one counts dinosaurs as endotherms). Marsupials almost bit it. Archaic birds were completely wiped out. Microfossils: rapid and profound extinction of forams (and others) at the K-T. All major marine reptiles wiped out: ichthyosaurs, mosasaurs, plesiosaur, pliosaurs Marine primary productivity: Jim Zachos (this dept.) and other identified a profound drop in primary productivity in the oceans around the K/T (using carbon isotope analysis of foram shells), and named the post-K/T ocean the 'Strangelove Ocean'.

## Consequences

**a.** Mammal diversification

b. Bird diversification