With the impending return of the lunar samples from the Apollo exploration of the Moon, NASA Administrator James Webb asked the National Academy of Sciences (NAS) to help build up a significant involvement by the university community in the development of NASA’s research programs. As a result, the NAS, with support from NASA, created the Lunar Science Institute (LSI) in 1968, as well as an independent national consortium, the Universities Space Research Association (USRA), to manage the LSI and other institutes and programs as needed.

Under the leadership of its first director, William W. Rubey, the LSI began a wide-ranging lunar research program that was characterized by close working relationships with scientists from NASA and the university research community. Much of the research was focused on the analysis of the lunar samples that were being returned during the Apollo explorations and what these samples and other data from the Apollo program could reveal about the geology and geophysics of the Moon.
One topic of interest was the formation and structure of lunar basins and craters. In 1976, the LSI sponsored a Symposium on Planetary Cratering Mechanics that was held in Flagstaff, Arizona, and the Institute compiled the material for the follow-on book, *Impact and Explosion Cratering.* Participants at the conference discussed a range of issues related to the formation of craters, including the extent to which crater shapes are determined by the make-up of the target body, from where in the vertical distribution of the target body do materials in the ejecta distribution come, how shock waves produced by the impact might create magnetism in the minerals of the rocks at the impact site, and many other topics related to the mechanics of cratering.

Additional research occurred in 1977, when Peter Schultz, a staff scientist at the LSI, began the management of the science associated with the operation of the Vertical Gun Range at NASA’s Ames Research Center. The facility allows the study of craters produced by the vertical gun, which produces a gunpowder explosion that compresses hydrogen gas, which in turn propels a marble-size pellet down a 14-foot barrel into a target. High-speed cameras record the development of the impact and its aftermath.

In 1978, the LSI was renamed the Lunar and Planetary Institute (LPI), reflecting the growing, common interests of the lunar and planetary research communities. One such area of common interest involved large impacts on some of the terrestrial planets that produced basins with outlying rings, so called multi-ring basins. In the fall of 1980, the LPI sponsored a *Conference on Multi-ring Basins: Formation and Evolution.* Peter Schultz and Carroll Ann Hodges of the U.S. Geological Survey convened the conference. Topics discussed at the conference included the possible mechanisms for creating the multi-ring structures, the time sequence...
of events during the formation, the density distribution of material within the structures, the profile of the underlying layers of material, and the range of the ejecta from the basins. The LPI published a book comprised of the research papers that were presented.2

That same year, Luis Alvarez, a Nobel-laureate physicist at the University of California, Berkeley, and the Lawrence Berkeley Laboratory, his son Walter Alvarez, a geologist, Frank Asaro, a nuclear chemist, and Helen Michel, a paleontologist, together published an article in Science magazine titled Extraterrestrial Cause for the Cretaceous-Tertiary Extinction.3 The group reported on finding large increases of the element iridium in deep-sea sediments that were exposed in Italy, Denmark, and New Zealand. The iridium was deposited in a thin clay layer that separated two distinct geological periods, the Cretaceous and the Tertiary (now called the Paleogene). This boundary between the Cretaceous and Paleogene periods is also the boundary between the Mesozoic and Cenozoic eras. Dinosaurs were prevalent during the Mesozoic era and extinct during the Cenozoic.

The Alvarez group proposed that the iridium came from an asteroid that impacted the Earth 65 million years ago, which is the time that marked the end of the Cretaceous period in geological history. They estimated the diameter of the asteroid at about 10 kilometers and that the impact would have injected about 60 times the asteroid’s mass into the Earth’s stratosphere, where it would be distributed worldwide and remain for several years. They proposed that the resulting darkness would suppress photosynthesis and cause the extinctions noted in the geological record. The Cretaceous-Paleogene boundary corresponds to one of the greatest mass extinctions in Earth’s history. At least 75 percent of the species on Earth were extinguished. In the oceans, more than 90 percent of the plankton was extinguished, which led to the collapse of the oceanic food chain.4

From its beginning, the LPI has sponsored annual conferences, now called the Lunar and Planetary Science Conferences, which are attended by hundreds of lunar and planetary researchers from around the world. In addition, the Institute sponsors workshops and topical conferences. A year after the publication of the paper by the Alvarez group, the LPI sponsored a topical conference titled The Conference on Large Body Impacts and Terrestrial Evolution: Geological, Climatological, and Biological Implications. The conference was co-sponsored by the U. S. National Academy of Sciences and held in Snowbird, Utah.

Peter Schultz was a part of the program committee for this first “Snowbird Conference,” as they came to be called.5 Among the more than 60 papers presented at the four-day conference was a paper by the Alvarez group and two papers co-authored by Peter Schultz. The majority of papers presented aimed to further explore the idea that had been presented by Luis Alvarez and
his colleagues. One was not. The abstract of the paper by Thomas J. M. Schopf of the University of Chicago read in part:

>The first step in any scientific program is to determine the problem to be solved. The often popular view that thousands of species of dinosaurs went extinct in the space of a year or two, worldwide, is not true. The firm evidence is that during the last 2 to 3 m.y. of the latest Cretaceous ... a total of about 16 species ... which had been living along the margins of a large seaway (which once extended from the Gulf of Mexico to the Arctic Circle) died off as the seaway dried up. Elsewhere in the world, local populations of dinosaurs had evidently died out before the latest Cretaceous both in Mongolia and in southern Europe. Possibly a species persisted in northern Europe into the latest Cretaceous. Seen in this light, the extinction of the dinosaurs is a perfectly understandable phenomenon – indeed no different than the fate of millions and millions of previous species. The reason why the extinction of the dinosaurs has attracted so much non-scientific attention by scientists and others is that (1) it doesn’t cost anyone anything, (2) it sounds impressive, (3) it’s basically a rather unimportant scientific problem though a rather important popular problem, and (4) hard paleontological data are difficult to obtain.6

The seaway referenced by Schopf is called the Western Interior Seaway, and his position was well established in the field of Paleobiology. In 1975, the dinosaur expert Robert T. Bakker had written in a Scientific American article that the likely reason for the extinction of the dinosaurs:

... is the draining of shallow seas on the continents and a lull in mountain-building activity in most parts of the world, which would have produced vast stretches of monotonous typography. Such geological events decrease the variety of habitats that are available to land animals, and thus increase competition. They can also cause the collapse of intricate, highly evolved ecosystems; the larger animals seem to be the more affected. At the end of the Permian similar changes had been accompanied by catastrophic extinctions among therapsids and other land groups. Now, at the end of the Cretaceous, it was the dinosaurs that suffered catastrophe; the mammals and birds, perhaps because they were so much smaller, found places for themselves in the changing landscape and survived.7

Schopf’s skepticism about the impact hypothesis as the cause of the extinctions at the end of the Cretaceous period was shared by many paleobiologists. In a 1981 paper titled, Out with a Whimper, Not a Bang, W. A. Clemens, J. David Archibald, and Leo J. Hickey pointed out:

... the global pattern of relatively few extinctions in the tropics with increasing frequency of exterminations to the north is just the reverse of what would be expected [under the Alvarez hypothesis]. Dormancy and carry-over mechanisms evolved in response to climatic stress and are assumed to have been, then as now, less well developed in the tropics. In addition, plants eliminated from northern floras are those of more tropical affinity, like palms. ... This multiplicity of patterns of extinction strongly argues against any hypothesis invoking some kind of catastrophic, short, sharp shock as the causal factor of the terminal Cretaceous extinctions. These paleobiological data suggest the Cretaceous-Tertiary transition was a period of several tens of thousands if not hundreds of thousands of years in duration, characterized by interaction of a complex of physical and biological factors producing a high net rate of decrease in biotic diversity within both the terrestrial and marine biotas.8
This was just the beginning of widespread resistance to the ideas of the Alvarez group by paleontologists. The acrimony was at times rather bitter, as suggested by the following quotation from Robert Bakker:

> The arrogance of these people is simply unbelievable. They know next to nothing about how real animals evolve, live, and become extinct. But, despite their ignorance, the geochemists feel that all you have to do is crank up some fancy machine and you've revolutionized science. The real reason for the dinosaur extinctions have to do with temperature and sea level changes, the spread of diseases by migration and other complex events. In effect, they're saying this: we high-tech people have all the answers, and you paleontologists are just primitive rockhounds.\(^9\)

We can hope that Bakker's charge of arrogance was overblown, but it was true that many geochemists were applying new technologies that had been developed for the analyses of lunar samples.

Meanwhile at the LPI, scientists were keeping their heads down as the controversies raged; continuing their research on crater formation, conducting workshops and conferences, and training new planetary scientists. The 1983 class of LPI Summer Interns contained an undergraduate from Indiana University, David Kring, who would later become involved in investigations that led to the identification of the crater that was caused by the kind of impact the Alvarez group had envisaged.

The discovery of the crater site was actually made at about the same time as the research by the Alvarez group, and it was announced the weekend before the first Snowbird Conference was held. Geophysicists Glen T. Penfield and Antonio Camargo-Zanoguera, working for the Mexican national oil company, Petróleos Mexicanos or PEMEX, gave a paper at the 51st annual meeting of the Society of Exploration Geologists in which they described a large, buried, circular structure on the northwestern margin of the Yucatán peninsula of Mexico.

A recent survey collected approximately 50,000 km of high sensitivity aeromagnetic data at 500 m altitude over the Campeche bank and Yucatan platform. In conjunction with gravimetric studies and data from three Pemex wells, this survey indicated the presence of two concentric zones of igneous material beneath the central Yucatan platform. The central zone, characterized by numerous high amplitude (approaching 1000 γ), short wavelength magnetic anomalies, and a gravity high, has a diameter of approximately 60 km and is centered near the town of Progreso on the northern Yucatan coast. Well data indicates the presence of massive andesites of Jurassic or Cretaceous age. Modeling the magnetic and gravity data indicates in excess of 3 km of high-density highly magnetic material in this central zone. The depth to the top of the zone is on the order of 1100 m below the ground surface. Concentric with this area is an outer zone characterized by low amplitude (5 to 20 γ), short wavelength magnetic anomalies, and a gravity low surrounded by a weak gravity high. This outer zone is approximately 200 km in diameter, and the well data suggest the presence of intercalated volcanics and limestones.\(^{10}\)

Among the possible explanations for the structure, Penfield and Camargo listed, “a mid-plate igneous plume, or astrobleme,” the latter being the scar left on the surface of the Earth by the impact of an asteroid or comet.
Penfield and Camargo were exploring for oil deposits when they had done their survey and analysis of PEMEX data. Such exploration was the primary interest of the members of the Society of Exploration Geologists, and their meeting was not attended by geologists and geophysicists who were involved in the exploration of the Moon and planets of our solar system. Thus, the initial discovery of what came to be called the Chicxulub crater was unknown to lunar and planetary scientists for the next ten years.

In the fall of 1984, the LPI held a conference in Kona, Hawaii, titled the Origin of the Moon, and the Institute subsequently published a book with the same title. An outcome of this conference was a near-consensus view by the lunar and planetary research community that the Moon was created by a collision of a Mars-size planetary body with the Earth very early in the history of the Earth. The presentations and discussions at the conference helped to open the minds of researchers to the inevitability of impacts. In a paper for the conference, William Hartmann of the University of Arizona wrote,

An example of the problem of class-predictable events in planetary science is the probable Cretaceous-ending asteroid impact. Since the 1960s, asteroid statistics have implied such events every few $10^7$ – $10^8$ years, but we could not convincingly tie specific geologic effects to specific impacts. In the absence of such evidence, impacts of this size tended to be ignored; as scientists, we should have pursued the geologic and climatic consequences of these class-predictable events instead of waiting for iridium-rich layers to take us by surprise.\textsuperscript{11}

Ever since the announcement of the impact hypothesis by the Alvarez group, many research groups had been searching for the impact site, although other research groups were looking for or studying large volcanic sources that might explain the extinctions at the end of the Cretaceous. In the spring of 1987, the LPI held its 18th annual Lunar and Planetary Science Conference in Houston, and reports of some of the searches and studies were given at the conference. Alan R. Hildebrand and William V. Boynton of the Lunar and Planetary Laboratory of the University of Arizona reported on their analysis of rare-earth-element abundances in the Cretaceous-Tertiary (K/T) impact fall-out layers at various sites around the globe. They suggested that the impact site was in the eastern Pacific Ocean basin.\textsuperscript{12}

A year later, however, a group of researchers led by Joanne Bourgeois of the University of Washington discovered an enormous tsunami deposit at sites near the Brazos River in Texas that were dated at the end of the Cretaceous period. The authors wrote:

Conditions for depositing such a sandstone layer at these depths are most consistent with the occurrence of a tsunami about 50 to 100 meters high. The most likely source for such a tsunami at the Cretaceous-Tertiary boundary is a bolide-water impact.\textsuperscript{13}

In the fall of 1988, the LPI co-sponsored with the National Academies of Science the second Snowbird conference, which had the title Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality. Various possible mechanisms for the end of the Cretaceous period were discussed at the conference, including the gradual transition favored by most paleontologists, as well as more catastrophic causes such as Earth impacts by asteroids or comets or large-scale volcanism episodes. Among the 60 talks and 67 posters given at the conference was a paper by Peter Francis, a visiting scientist at the Institute and Kevin Burke, who was the Director of the LPI. These LPI researchers discounted volcanism as a cause unless large episodes might have triggered ocean current circulation patterns that would cause global climatic changes. The Alvarez group gave a presentation, in which they wavered a bit about the certainty of an asteroid impact as the sole cause of the end of the Cretaceous period, perhaps because they yet knew of no suitable impact crater to support their hypothesis. Paleontologists J. David Archibald and Laurie Bryant reported on their examination of the vertebrate record, concluding:

The extinction patterns among the vertebrates do not appear to be attributable to any single cause, catastrophic or otherwise. The earliest Paleocene fauna can be understood as a Late Cretaceous fauna simply altered by withdrawal of the Western Interior Sea and by the formation of extensive swamps that replaced well-drained terrestrial environments.\textsuperscript{14}
In a paper at the conference, Hildebrand and Boynton continued to favor an oceanic impact but now argued that the putative impact occurred in the ocean near North America.

All available evidence is consistent with an impact into oceanic crust terminating the Cretaceous Period. Although much of this evidence is incompatible with endogenic origin, some investigators still feel that a volcanic origin is possible for the K/T boundary clay layers. Following the dictum that remarkable hypotheses require extraordinary proof this latter view may still be reasonable, especially since the commonly cited evidence for a large impact stems from delicate clay layers and their components (i.e., no catastrophic deposits), and the impact site has not yet been found.

Impact sites have been suggested all over the globe, but are generally incompatible with known characteristics of the boundary clay layers. We feel the impact is constrained to have occurred near North America by: the occurrence of a 2 cm thick ejecta layer only at North America locales, the global variation of shocked quartz grain sizes peaking in North America ... and possibly uniquely severe plant extinctions in the North American region. Also the ejecta layer may thicken from north to south.... A new constraint on the impact location comes in the form of impact wave deposits; giant waves are a widely predicted consequence of an oceanic impact.

Impact wave deposits have not been found elsewhere on the globe, suggesting the impact occurred between North and South America. Finally, in the spring of 1990, Alan Hildebrand connected with Glen Penfield, and the two of them, together with David Kring, Mark Pilington, Antonio Camargo-Zanoguera, Stein B. Jacobsen, and William Boynton collected the magnetic and gravity-field data, some of the core samples from previous PEMEX drillings, and the data from analysis of ejecta from sites around the Caribbean. In the fall of 1991, they published a paper in the journal Geology titled Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. In the paper, they concluded:

The Chicxulub crater is the largest probable impact crater on Earth. Its position and target-rock composition satisfy many of the characteristics required for the K/T crater, and it may have a K/T boundary age. This impact may have caused the K/T extinctions.

Hildebrand and his colleagues found shocked quartz grains in Chicxulub rocks, indicative of an impact, but they were unable to precisely date the Chicxulub crater.

The next year, a team led by Buck Sharpton that included Graham Ryder and Benjamin Schuraytz of the LPI, Brent Dalrymple of the U. S. Geological Survey, and Luis Marín and Jaime Urrutia-Fucugauchi of the Universidad Nacional Autónoma de México (UNAM) published a paper based on their analyses of PEMEX core samples. They measured enhanced concentrations of iridium in some of the sections of the core samples, and they were able to determine the age of some of the melt-rock samples as 65.2±0.4 million years at the 95% confidence level. For many researchers, this measurement, coupled with an independent and identical result the same year by Paleontologist Carl C. Swisher III ended any remaining uncertainty about whether or not the buried Chicxulub structure was the long-sought impact crater that had been postulated by the Alvarez group in 1980.
Sharpton and Paul Spudis at the LPI, and their colleagues at the University of Houston, UNAM, and PEMEX continued to study the Chicxulub structure through a cooperative research agreement between the LPI and the Instituto de Geofisica of UNAM. Building on their accumulated knowledge of lunar and planetary crater structures over many years, Sharpton and his colleagues published an article in Science magazine in the fall of 1993 with the following abstract:

The buried Chicxulub impact structure in Mexico, which is linked to the Cretaceous-Tertiary (K-T) boundary layer, may be significantly larger than previously suspected. Reprocessed gravity data over Northern Yucatán reveal three major rings and parts of a fourth ring, spaced similarly to those observed at multi-ring basins on other planets. The outer ring, probably corresponding to the basin’s topographic rim, is almost 300 kilometers in diameter, indicating that Chicxulub may be one of the largest impact structures produced in the inner solar system since the period of early bombardment ended nearly 4 billion years ago.20

In 1994, the LPI sponsored the third Snowbird Conference, which was actually held in Houston, Texas, and titled New Developments Regarding the K/T Event and Other Catastrophes in Earth History. The follow-on publication was co-edited by Graham Ryder, David Fastovsky, and Stefan Gartner and was titled The Cretaceous-Tertiary Event and Other Catastrophes in Earth History.

At the conference, the impact data were well presented by the Alvarez, Hildebrand, and Sharpton research groups. The dissenters, while admitting the reality of the impact, were reaching other conclusions about the KT extinctions. For example, J. David Archibald wrote, “Single-cause theories of extinction, such as a bolide impact and its corollaries, fail to explain the pattern of vertebrate extinctions at the KT boundary.”21 José Guadalupe Lopez-Oliva & Gerta Keller added, “Our study indicates that the biotic effects of the KT boundary event on planktic foraminifera in the northeastern Mexico sections were not as catastrophic as predicted from a large bolide impact on Yucatan.”22 In a separate paper, Keller argued:

One of the most important recent developments in KT boundary studies is the growing awareness that (1) the mass extinction associated with this event is not the result of a single catastrophe, (2) that extinctions occurred over an extended time period and were selective rather than random within organismal groups as well as between different groups, and (3) that the biotic effects were most severe and sometimes limited to tropical-subtropical regions while high-latitude faunas and florals escaped virtually unscathed.23

The LPI’s Graham Ryder wrote an article for the follow-on book that responded to the conclusions made by many of the paleontologists:

Many counter-revolutionary papers (i.e., those that deny an impact cause) over the last decade ... give the impression that it is those who invoke an impact who have required a particular paleontological significance, for instance that impact proponents claim abrupt extinction. Yet it was never the case that an impact was inferred and that then there was a search for associated extinctions. It is an ironic reversal that some paleontologists chose to reduce the significance of the boundary after the impact was inferred. Rather than evaluate the record in the light of an impact, they chose to construct straw men.24

Reprocessed gravity data over Northern Yucatán reveal three major rings and parts of a fourth ring, spaced similarly to those observed at multi-ring basins on other planets. 20

The impact site had been located and its structure continued to be examined by additional drillings, some of which were conducted through the collaborations between the LPI and UNAM. However, the argument as to whether or not the impact caused the extinctions at the end of the Cretaceous persisted.
This extraordinary event has led to new kinds of thinking in every branch of science it has touched...In geology, it forced a reevaluation of the central geological doctrine of “uniformitarianism” or “gradualism,” which for 150 years had discouraged any thinking about catastrophic events.

In 2010, Kring joined 40 other senior researchers from 12 countries in the publication of a review article for Science magazine titled *The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary.* Following their world-wide, exhaustive research, the authors concluded:

> The Cretaceous-Paleogene boundary ~65.5 million years ago marks one of the three largest mass extinctions in the past 500 million years. The extinction event coincided with a large asteroid impact at Chicxulub, Mexico, and occurred within the time of Deccan flood basalt volcanism in India. Here, we synthesize records of the global stratigraphy across this boundary to assess the proposed causes of the mass extinction. Notably, a single ejecta-rich deposit compositionally linked to the Chicxulub impact is globally distributed at the Cretaceous-Paleogene boundary. The temporal match between the ejecta layer and the onset of the extinctions and the agreement of ecological patterns in the fossil record with modeled environmental perturbations (for example, darkness and cooling) lead us to conclude that the Chicxulub impact triggered the mass extinction.

However, this extraordinary event has led to new kinds of thinking in every branch of science it has touched. In biology, it required thinking about non-Darwinian mechanisms of evolution. In geology, it forced a reevaluation of the central geological doctrine of “uniformitarianism” or “gradualism,” which for 150 years had discouraged any thinking about catastrophic events. In chemistry, it focused on iridium, an almost comically obscure element, and created a demand for very fast analytical capabilities at the parts-per-trillion level. And new problems have been opened up in ecology, geophysics, astrophysics and atmospheric science, as well.

The Chicxulub research effort continues with additional drillings and studies by Kring and others at the LPI. As noted by Alvarez, it is an important investigation affecting many branches of science. The LPI has played a significant role in the development of this research, consistent with the vision of NASA Administrator Webb and others who created USRA to be an entity in and through which universities could cooperate with each other, the federal government, and other organizations to develop knowledge.
1 Following the retirement of NASA's Donald Gault, who had initiated the effort.

2 Schultz co-authored papers for the conference, as did Steven Croft of the LPI, and Roger Phillips, who was then the Director of the Institute.


5 Topics in the call for papers for the first Snowbird Conference included (1) the nature and flux of near-Earth objects and the geological evidence of their interactions, (2) physics of high-energy impacts, (3) the biological record and evidence for catastrophic extinction, (4) searching the extensive geological record for physical evidence of major impacts, and (5) meteorological and climatological consequences of large-scale impacts.


26 Ibid, p. 1214