North Dakota's Role in the K/T Boundary Controversy

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Note: Most scientific articles now refer to the K-T boundary as the K-Pg boundary. The replacement of Tertiary with the Paleogene (23 – 65.5 million years ago) and the Neogene (2.6 -- 23 million years ago) prompted this change. Since this is an article meant for the general public, I stayed with the old terminology to minimize confusion.

Asteroid Impact Theory

Throughout the billions of years of Earth's geologic history, time has been marked by relatively slow change. The fossil record documents the evolution and adaption of species over time, the rise of new species never before seen on Earth, and the extinction of others. Major extinction events, so named because they mark a time in Earth's past when a high percentage of species throughout the world appear to have become extinct at the same time, geologically speaking, have always fascinated geologists. One of the five greatest extinction events in Earth's history occurred 65.5 million years ago at the end of the Cretaceous Period when approximately 70% of all species on Earth, both on the land and in the sea, disappeared from the rock record. This event is also of interest to the general public because it includes the extinction of the last of the dinosaurs which people, both young and old, find fascinating.

Although dinosaurs had been dominant on Earth for 160 million years, generations of geologists like my father and I were taught dinosaurs became extinct at the end of the Cretaceous Period because they could not adapt quickly enough to a changing world. We were told a sharp drop in global temperatures and/or an abrupt change in the plants they consumed may have led to their demise (Dunbar, 1957). Then, in 1980, Walter Alvarez and his father Louis Alvarez (along with Frank Asaro and Helen Michel) concluded dinosaurs and many other forms of life became extinct at the end of the Cretaceous due to an asteroid impact. They based their theory on the presence of abnormally high concentrations of iridium (a metal in the platinum family that is more plentiful in extra-terrestrial bodies than it is on Earth) in rocks at the K-T boundary (the boundary between the Cretaceous and Tertiary geologic periods) in Italy and Denmark. Based upon four criteria, including the amount of iridium and the amount of ejecta in the Cretaceous-Tertiary (K-T) boundary clay, they estimated the asteroid would have to have been approximately 6.2 miles (10 km) wide and would have created a crater more than 62 miles (100 km) in diameter.

The asteroid has been calculated to have impacted Earth with a force variously estimated at 100 trillion tons of TNT, 10,000 times the World's nuclear arsenal at the height of the Cold War, or seven billion Hiroshima-sized atom bombs. Walter Alvarez (1997) described the utter devastation brought on at the moment of impact, the creation of the impact crater, a tsunami in the Gulf of Mexico, and a boiling, churning atmosphere near the impact that ignited all trees and cooked all animals not sheltered under rocks or in holes when wildfires swept across the lands. It may only have taken a few hours for the expanding fireball from the impact site to be distributed around Earth and the earthquake generated by the impact caused the planet's surface to rise in waves hundreds of feet high as much as 620 miles (1,000 km) from ground zero (Powell, 1998). Powell wrote, "A few minutes later, the mixture of vaporized meteorite and rock, still traveling at ballistic velocities of 3.1-6.2 mi/sec (5 km/sec to 10 km/sec), began to reenter the atmosphere. The individual globules were traveling so fast that they ignited, producing a literal rain of fire. Over the entire globe, successively later the greater the distance from the target, the lower atmosphere burst into a wall of flame, igniting everything below…Everything that could burn did." Schulte and others (2010) agree that the forest communities were devastated, but question whether the "thermal pulse" caused by the atmospheric reentry of the ejecta spherules would have been sufficiently high to ignite the woody biomass. Dust generated by the impact was dispersed in the upper atmosphere throughout the world blocking out sunlight, the darkness and cold lasting anywhere from months to years. As a result, the photosynthesis-based food chain collapsed. When light was finally able to penetrate the darkness the sun's heat was trapped in the carbon dioxide-rich atmosphere for possibly thousands of years. Acid rain fell from the sky as precipitation mixed with nitrogen and sulfur compounds in the atmosphere (Powell, 1998). Of the impact aftermath, Alvarez (1997) wrote "A world first dark and frozen, then deadly hot, a world poisoned by acid and soot." Little wonder so many forms of life perished under these conditions.

Artist's rendition of the K-T impact courtesy of Don Davis.

The K-T Boundary Controversy

The Alvarez theory was the catalyst for a number of scientists to study the K-T boundary throughout the world in an effort to find evidence supporting or rejecting the asteroid impact theory as the cause of the mass extinction event. In fact, for the next ten years the impact theory was one of the most hotly debated scientific theories in recent time. Between 1980 and 1990, 2,000 scientific papers were written regarding the K-T extinction event (Alvarez, 1997).

The K-T boundary in North Dakota approximates the contact between the Hell Creek Formation (Cretaceous) and the overlying Ludlow Formation (Paleocene). That is, the Hell Creek Formation consists of rocks that are from the Upper Cretaceous and the Ludlow Formation includes rocks from the lowest Tertiary or Paleocene (figs. 1 and 2). Because the K-T boundary is a measurement of time and the contact between the Hell Creek and Ludlow Formations marks a separation between two sets of rock units based on observable field criteria or signatures on electric logs in the subsurface, the two are not interchangeable. While the formational contact and the time boundary are coincident in some localities, in others they can be 10 or more feet apart. This comparison is made all the more difficult when the contact is subtle between the dinosaur-bearing rocks of the Hell Creek Formation and the overlying nondinosaur-bearing Ludlow Formation.

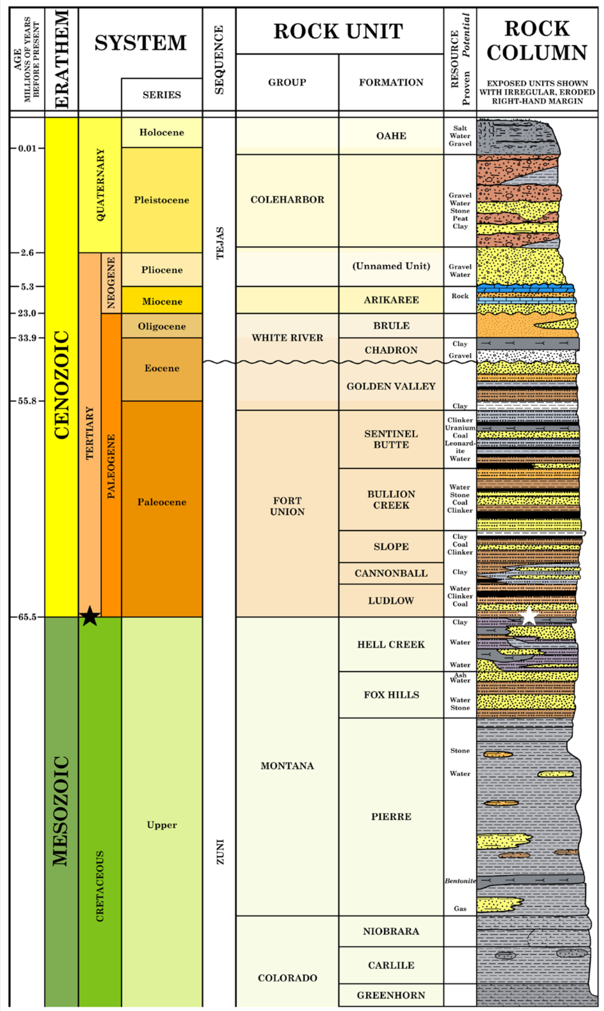

Figure 1. A stratigraphic column of the rocks and sediments exposed at the surface in North Dakota. (Murphy et al., 2009) The black star marks the K-T boundary and the white star the Hell Creek/Ludlow contact.

The top of the Hell Creek can be defined as occurring at the top of the highest bentonitic bed. On the other hand, the base of the Ludlow can be defined as the bottom of the first persistent lignite. However, Murphy and others (1995, 2002) determined the Hell Creek-Ludlow contact occurred at lignites less than half of the time in south-central North Dakota. Additionally, more subtle criteria can be used to identify the contact; Hell Creek rocks are typically more somber in color than the overlying Ludlow rocks, there is often a change in slope at the contact because the rocks of the Ludlow Formation are less resistant to erosion and therefore form gentler slopes, rocks of the Ludlow Formation tend to be covered with vegetation whereas Hell Creek rocks are often barren, Hell Creek rocks tend to be obscurely bedded while the Ludlow rocks contain more observable bedding, and organic-rich mudstones in the Hell Creek are characteristically reddish-brown in color and have a paper-like fabric while Ludow mudstones are dark brown and have a higher clay content. Walter Moore, a geology professor at the University of North Dakota from 1960 to 1981 spent several summers mapping Hell Creek and Ludlow strata in Bowman and Slope counties. During a presentation of his work in the late 1970s, Professor Moore stated there was no substitute for experience – that you have to develop a feel for the rocks when you are working with the Hell

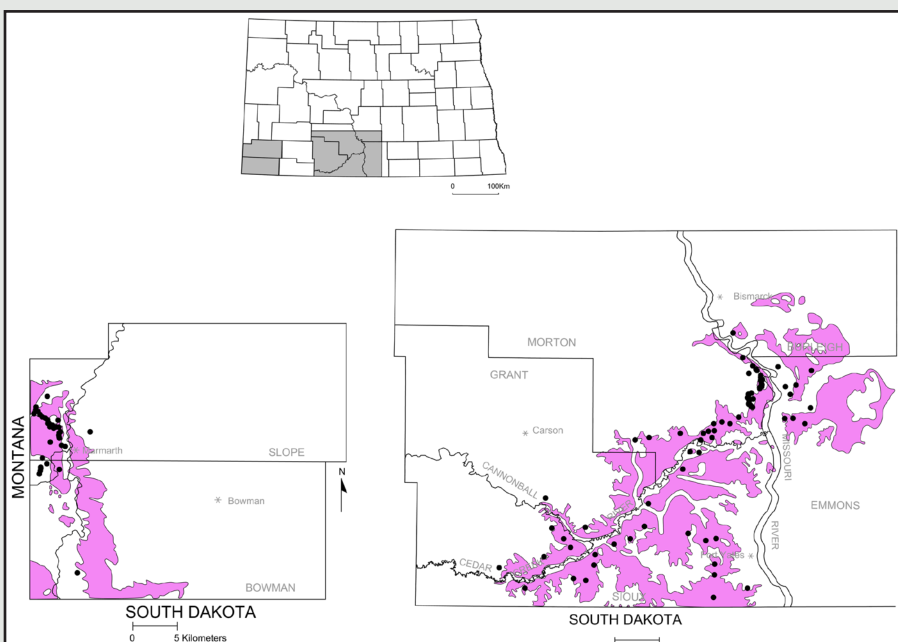

Figure 2. The location of Hell Creek rocks (purple) in south-central and southwestern North Dakota. Dots are the locations of 130 geologic sections measured by NDGS geologists (Murphy et al., 1995; Hoganson and Murphy 2002; Murphy et al., 2002).

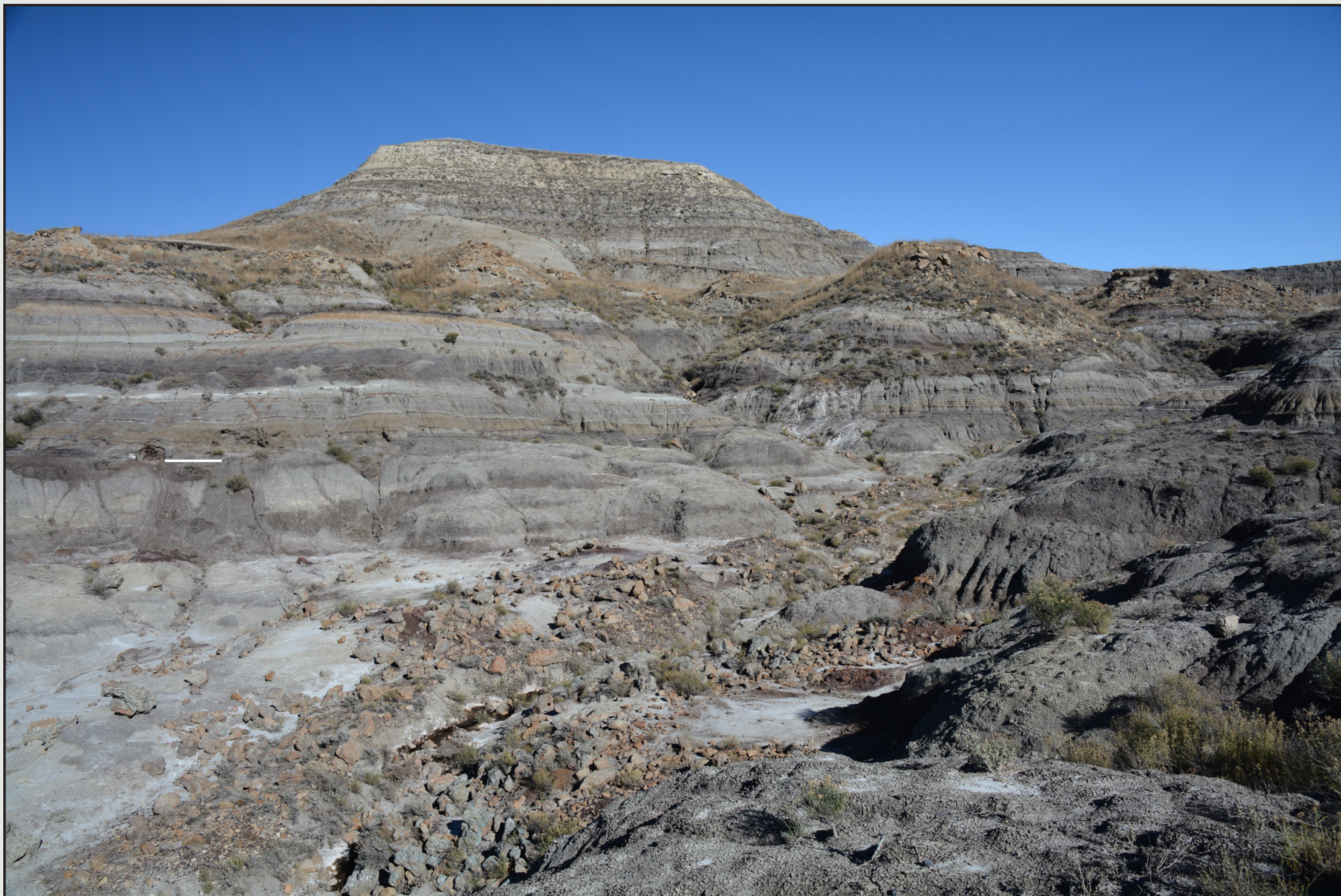

Figure 3. Mud Buttes in Bowman County, North Dakota. Although a distinct color change occurs in the top one fourth of the rocks in this photo, the contact between the Hell Creek and Ludlow Formations (white line) occurs one fourth of the way up from the base of the exposed rocks. The contact in this area occurs at a change in slope, at the top of the well-developed swelling claystones (bentonites), at the base of a thin coal, and the base of well-bedded strata.

Creek and Ludlow Formations. While this could be said about many things in geology and, for that matter, many things in life, it is particularly appropriate when determining the Hell Creek\Ludlow contact. The formational contact at a given locality may fit only one of the lithologic criterian noted in the preceding paragraph while a locality a mile away may fit all the criteria (fig. 3).

In 1984, Bruce Bohor and others discovered shocked mineral grains in the K-T boundary clay in eastern Montana. Prior to this, shocked quartz was only known to be present in and around established meteorite craters and at nuclear explosion sites. This discovery provided additional support for the asteroid impact theory. In the early 1980s, Bohor and Don Triplehorn sampled rocks along the Hell Creek\Ludlow contact in North Dakota, but were unable to find shocked quartz. In 1989 shocked quartz was found at Pyramid Butte in Slope County, North Dakota (Johnson et al., 1989). In 1995, we (Murphy et al.) were unable to detect shocked quartz in rocks spanning the K-T boundary in south-central North Dakota. In 2000, a team of scientists (including myself) reported shocked quartz from the K-T boundary clay at Mud Buttes in Bowman County, North Dakota (Nichols et al., 2000).

In 1981, Smit and Klaver reported finding small, rounded grains or spherules in a K-T boundary clay in Spain. These were identified as congealed droplets of molten material that had been blasted into the atmosphere during the meteorite impact (Montanari et al., 1983). These ejection spherules were first discovered in North Dakota at Mud Buttes in 2000 (Nichols et al., 2000). In at least one locality in Mud Buttes the spherules are contained within a bright orange claystone that is up to one-and-one-half inches (3.8 cm) thick (figs. 4-6).

Iridium, whose relatively high concentrations at the K-T boundary in Italy were the catalyst for the impact theory, has been reported from both Pyramid Butte (Johnson et al., 1989) and Mud Buttes (Nichols and Johnson, 2008) in southwestern North Dakota. Iridium was found above the K-T boundary at Huff in Morton

Figure 4. The bright orange claystone containing spherules (white arrow) is present at the K-T boundary in this photograph taken at Mud Buttes.

Figure 5. A close up of the K-T boundary clay at Mud Buttes. Iridium and shocked quartz grains have been found in the upper part of the boundary clay (Bercovici et al., 2013). This is consistent with the two layer K-T boundary clay (spherule layer overlain by a shocked quartz and iridium layer) typically found in the western United States (Alvarez, 1997).

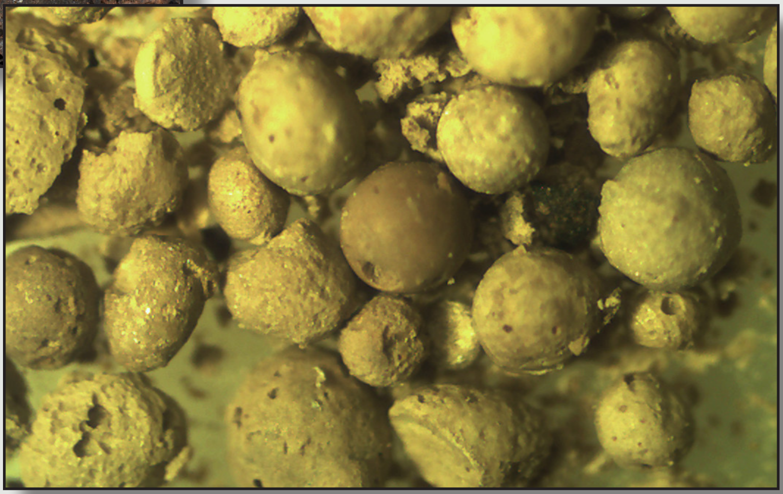

Figure 6. A photomicrograph of spherules (approximately 0.5 mm diameter ejecta from the Chicxulub Crater) separated from the bright orange claystone at Mud Butte.

Figure 7. Sixty-six million year old leaf fossils in the Hell Creek at Mud Buttes collected from a locality previously sampled by Kirk Johnson.

County, North Dakota, but likely resulted from reworking (Murphy et al., 1995).

Over the years, a set of criteria has been developed to identify the terrestrial K-T boundary clay. In their book, Nichols and Johnson (2008) listed a dozen of these criteria including the presence of shocked mineral grains, a boundary claystone (scientists have calculated that the boundary clay was deposited in less than 100 years, an instantaneous episode in geologic terms), an iridium spike, a fern spike (ferns are opportunistic and grow where other species are no longer present), along with Cretaceous and Tertiary fauna and flora (including palynomorphs - pollen of angiosperms, gymnosperms, spores of ferns and crytograms, and fungal spores), and magnetostratigraphy. They noted 100 terrestrial K-T boundary sections throughout the World that used at least one of these criteria to identify the boundary, 28 of these sites were from North Dakota. Nichols and Johnson (2008) pointed out the Williston Basin contains the best exposed and most studied section of Upper Cretaceous rocks in the world, accounting for 39% of the known terrestrial K-T boundary sites. Leaf fossils as well as fossil pollen have played an important role in the impact theory debate. Individually and collectively, Doug Nichols and Kirk Johnson amassed more than 22,000 leaf fossils from 160 sites and 700,000 palynomorphs from 24 measured sections in southwestern North Dakota (fig. 7). Evaluating leaf fossils, Wilf and Johnson (2004) placed the megafloral (leaf fossil) extinction at the K-T boundary at 57%. Nichols and Johnson (2008) evaluated palynomorphs across this boundary and determined the extinction rate for each of their palynological localities ranged from 17-30%.

Chicxulub Crater

Much of the intrigue in the 1980s focused on finding the impact crater and resolving the dispute between those scientists who believed extinction was caused by an asteroid impact and those who attributed the extinction event to volcanoes, greenhouse gases, etc. The search would consume 11 years before the Chicxulub crater was found on the Yucatan Peninsula, some 2,000 miles removed from North Dakota (fig. 8). The Chicxulub Crater is a 111- 124 mile (180 – 200 km) diameter structure buried beneath a half mile of sedimentary rock. At the time the asteroid hit, the Chicxulub area was covered by a shallow sea. While a few scientists continue to raise doubts about the impact theory, the doubters have largely been silenced by the mass of data supporting the theory that has been generated since it was first proposed in 1980. Thirty years after the impact theory was first put forward by the Alvarez's, an international panel of 41 scientists reviewed the data and concluded the Chicxulub impact triggered the mass extinction at the end of the Cretaceous

Figure 8. Map showing the position of the Chicxulub Crater in relationship to North Dakota.

Period (Schulte et al., 2010). Among the distinguished scientists on the K-T boundary panel were Kirk Johnson and Doug Nichols who had spent considerable time over the years studying the K-T boundary in North Dakota. In their book (Nichols and Johnson, 2008) they write "Southwestern North Dakota is not where the first investigations of floral changes across the K-T boundary were conducted, but it is the area that has seen the most intensive study, and from which the most complete record of these changes comes."

For several decades the Hell Creek and Ludlow rocks in southwestern North Dakota played an important role in the K-T impact debate. In addition, K-T researchers provided economic stimulus to this rural area by obtaining food and lodging in Marmarth and also purchasing their groceries, supplies, and fuel in the towns of Rhame and Bowman. For example, the Milwaukee Museum's Dig-a-Dinosaur Program brought a total of 150 volunteers to eastern Montana and southwestern North Dakota over portions of three summers (1986-1988) to record the proximity of dinosaur fossils to the K-T boundary (Barreto et al., 2003).

Although the debate has lessened in intensity, geologists continue to return year after year to southwestern North Dakota to learn more about this interesting time in Earth's geologic past. Without question, the rocks in North Dakota played a prominent role in answering the age-old question "Why, after dominating life on Earth for so long, did the dinosaurs become extinct?"

References

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

Alvarez, W., 1997, *T. rex* and the crater of doom: Princeton University Press, Princeton, N.J., 185 p.

Barreto, C., Fastovsky, D.E., Sheehan, P.M., 2003, A model for integrating the public into scientific research: Journal of Geoscience Education, v. 50, no. 1, pp. 71-75.

Bercovici, A, A., Hunter, J., Knauss, G., Wood, J., and Pearson, D. A., 2013, Out with the old, in with the new – vertebrate microstratigraphy documenting the immediate K–Pg mass extinction recovery: 73rd Society of Vertebrate Paleontology Annual Meeting, p. 85.

Bohor, B.F., Foord, E.E., Modreski, P.J., and Triplehorn, D.M., 1984, Mineralogic evidence for an extraterrestrial impact event at the Cretaceous-Tertiary boundary: Science, v. 224, pp. 867 – 869.

Dunbar, C.O., 1957, Historical geology: John Wiley & Sons, New York, 573 p.

Hoganson, J.W., and Murphy, E.C., 2002, Marine Breien Member (Maastrichtian) of the Hell Creek Formation in North Dakota – Stratigraphy, vertebrate fossil record, and age, *in* Hartman, J.H., Johnson, K.R., and Nichols, D.J., eds., The Hell Creek Formation and the Cretaceous-Tertiary boundary in the Northern Great Plains – an integrated continental record of the end of the Cretaceous: Geological Society of America Special Paper 361, pp. 247-270.

Johnson, K.R., Nichols, D.J., Attrep, M., Jr., and Orth, C.J., 1989, High-resolution leaf-fossil record spanning the Cretaceous-Tertiary boundary: Nature, v. 340, no. 6236, pp. 708-711.

Montanari A., Hay, R.L., Alvarez, W., Asaro, F., Michel, H.F., Alvarez, L.W., and Smit, J., 1983, Spheroids at the Cretaceous -Tertiary boundary are altered impact droplets of basaltic composition: Geology, vol. 11, pp. 668-671.

Murphy, E.C., Nichols, D.J., Hoganson , J.W., and Forsman, N.F., 1995, The Cretaceous-Tertiary boundary in south-central North Dakota: North Dakota Geological Survey Report of Investigation no. 98, 74 p.

Murphy, E.C., Hoganson, J.W., and Johnson, K.R., 2002, Lithostratigraphy of the Hell Creek Formation in North Dakota, *in* Hartman, J.H., Johnson, K.R., and Nichols, D.J., eds., The Hell Creek Formation and the Cretaceous-Tertiary boundary in the Northern Great Plains – an integrated continental record of the end of the Cretaceous: Geological Society of America Special Paper 361, pp. 9-35.

Murphy, E.C., Nordeng, S.H., Juenker, B.J., Hoganson, J.W., 2009, North Dakota stratigraphic column: North Dakota Geological Survey Miscellaneous Series no. 91.

Nichols, D.J. and Johnson, K.R., 2008, Plants and the K-T Boundary: Cambridge University Press, Cambridge, UK, 280 p.

Nichols, D.J., Murphy, E.C., Johnson, K.R., and Betterton, W.J., 2000, A second K-T boundary locality in North Dakota verified by palynostratigraphy and schocked quartz: Geological Society of America Abstracts and Programs, v. 32, no. 7, p. 130.

Powell, J.L., 1998, Night comes to the Cretaceous – Dinosaur extinction and the transformation of modern geology: W.H. Freeman and Company, New York, N.Y., 250 p.

Schulte, P., and others, 2010, The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary: Science, v. 327, pp. 1214-1218.

Smit, J., and Klaver, G., 1981, Sanidine spherules at the Cretaceous – Tertiary boundary indicate a large impact event: Nature v. 292, pp. 47-49.

Wilf, P. and Johnson, K.R., 2004, Land plant extinction at the end of the Cretaceous – quantitative analysis of the North Dakota magafloral record: Paleobiology, v. 30, pp. 347-368.