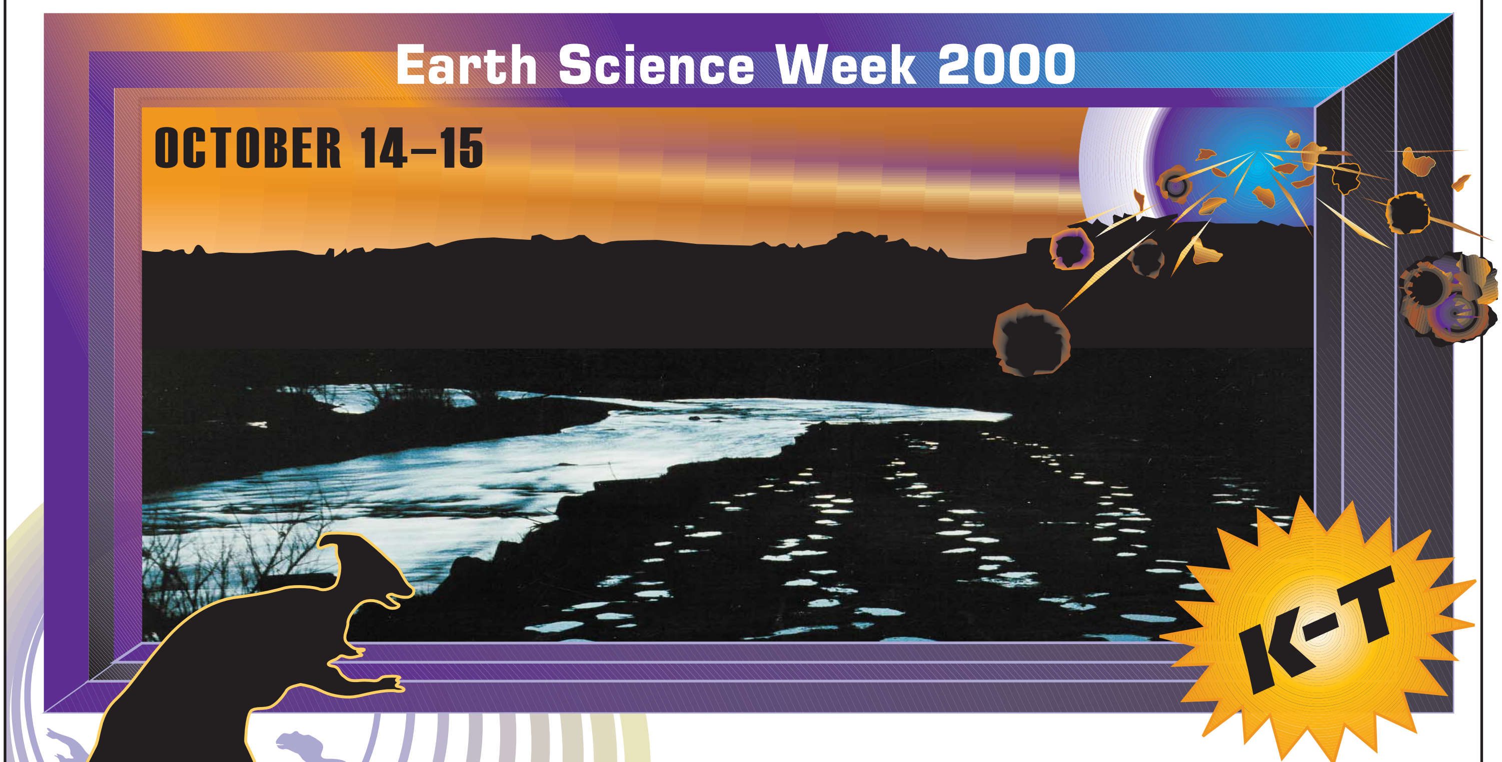
FIELD TRIP GUIDEBOOK

A DASH WITH THE DINOSAURS

A Mountain Bike Trek to the Purgatoire River Dinosaur Trackway and the Cretaceous–Tertiary Boundary Impact Layer of Southeastern Colorado

La Junta and Trinidad, Colorado

Edited and compiled by Matthew L. Morgan



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FIELD TRIP GUIDEBOOK

A Dash with the Dinosaurs: A Mountain Bike Trek to the Purgatoire River Dinosaur Trackway and the Cretaceous–Tertiary boundary Impact Layer of Southeastern Colorado

La Junta and Trinidad, Colorado

FOR EARTH SCIENCE WEEK 2000

OCTOBER 14 and 15, 2000

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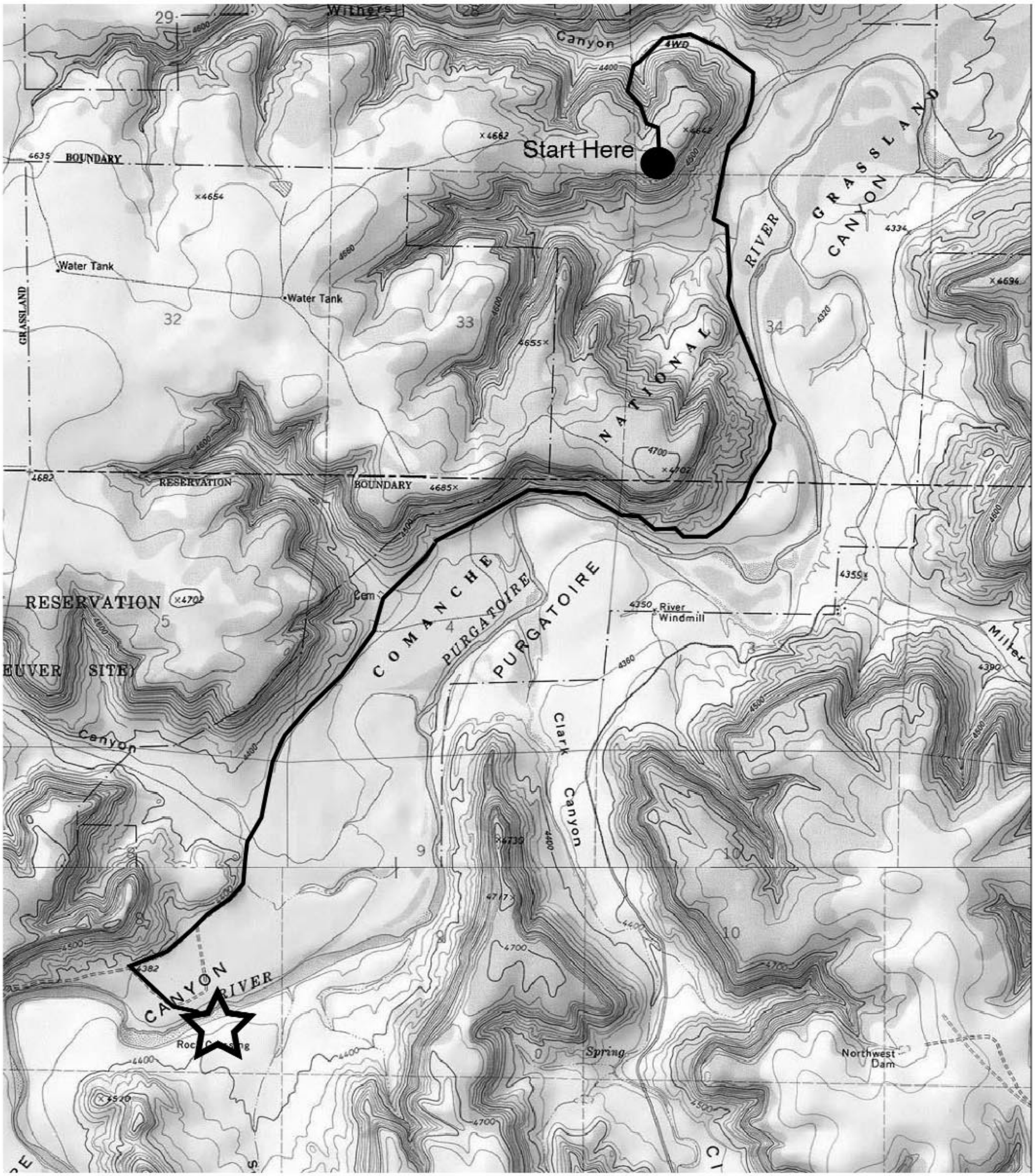

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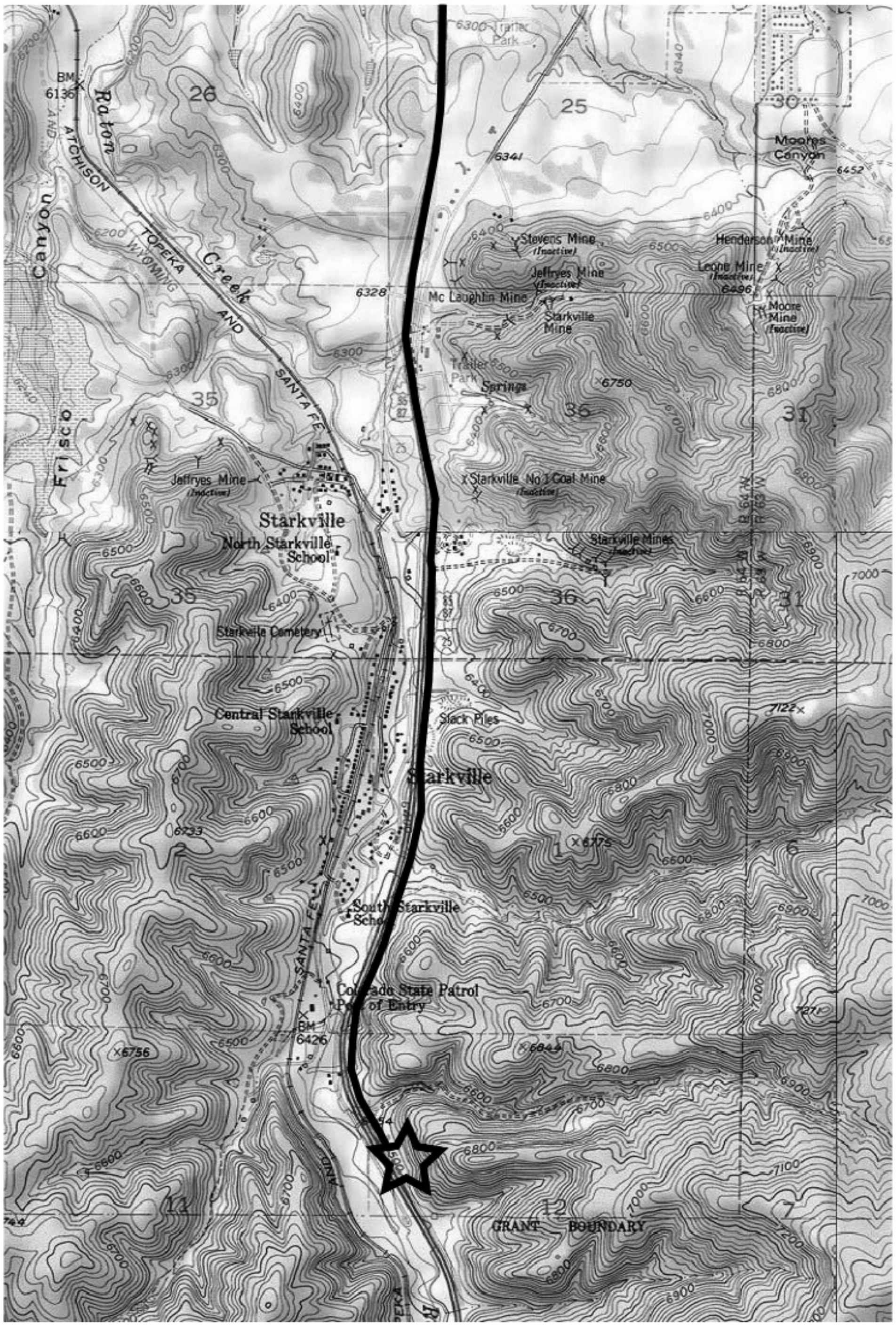
1 mile

Auto Route to Starkville K/T Boundary SIte

To Trinidad 1.17 mi



1 mile

A Guide to the Purgatoire Dinosaur Trackway
Excerpts from the Book *Dinosaur Lake*

By Martin G. Lockley, Barbara J. Fillmore, and Lori Marquart
Special Publication 40, Colorado Geological Survey, 1997
Guide edited by Matthew L. Morgan

INTRODUCTION

The Purgatoire River rises in the Rocky Mountains west of Trinidad, Colorado, and flows northeast across the southern High Plains for a distance of about 150 miles to its confluence with the Arkansas River just east of Las Animas. Although a sparsely populated and little known area, the Purgatoire Valley is one of the most beautiful locations on the High Plains. This guidebook will focus on the story of one small stretch of this valley known as Picket Wire Canyonlands, an area containing the largest dinosaur tracksite currently known in North America. The Picket Wire Canyonlands lie within the Comanche National Grasslands (Figure 1), approximately 23 miles south of the town of La Junta in southeastern Colorado. The area, currently managed by the U.S.D.A. Forest Service, is rich in history, flora and fauna, and above all has a unique paleontological heritage. The tracksite is located in the northern portion of the Canyonlands, and the track-bearing rock is situated both within, and on the banks of the Purgatoire River.

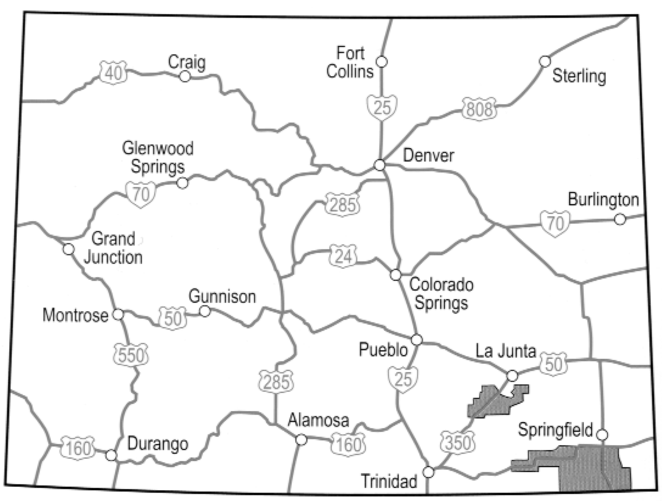


Figure 1. Location of the Comanche National Grasslands in Colorado. The Picket Wire Canyonlands are located south of La Junta on State Highway 350.

It was not until the 1930s that the Purgatoire site and several other important dinosaur tracksites in the western USA were even discovered. Even then, the full potential and significance of the tracksites was not realized. The Purgatoire Tracksite was studied in detail for the first time between 1982 and the present and has been described in scientific literature. In fact, the Purgatoire site alone was shown to yield four track-bearing layers containing at least 1300 footprints, representing a minimum of a hundred animals, mainly sauropods and theropods (see Figure 2). Sauropods are the group of large, long-necked creatures that are commonly referred to in general as "brontosaurs." Theropods are the two-legged, carnivorous dinosaurs such as Allosaurus. These tracks represent a larger number of dinosaurs than has been found at almost any other single dinosaur site in the Morrison Formation.

The site is currently the largest continuously mapped fossil footprint site in North America—perhaps the world. Among the more significant discoveries from the Purgatoire tracksite, discussed in further detail below, are the following:

- some of the world's longest trackways
- the world's first report of brontosaur tracks
- evidence of herding or social behavior

Figure 2. Illustration of the long-necked sauropods, commonly referred to as "brontosaurs." The short-legged, theropod carnivorous dinosaur Allosaurus is shown grazing near the river.

GEOLOGY

The dinosaur tracksite lies along the Purgatoire River within the floodplain of a wide canyon named the Picket Wire Canyonlands. The Picket Wire Canyonlands is divided into four geographically separate areas referred to as the Southern, Middle, and Northern Tracts, and the Upper Tier. The dinosaur tracksite is located in the Northern Tract and this area is referred to as the Purgatoire Tracksite throughout this guidebook. The Northern Tract reveals only Jurassic and Cretaceous rocks as seen in Figure 3.

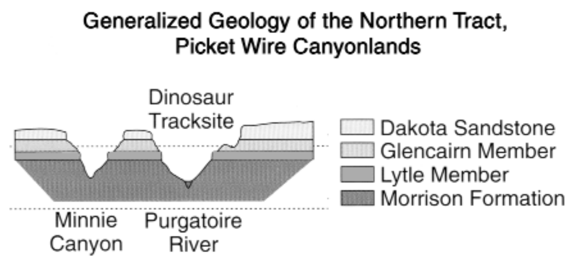


Figure 3. Cross section of strata showing the geology found in the Northern Tract of the Picket Wire Canyonlands.

- evidence that brontosaurs trampled clams and extensively disturbed the soils and substrates beneath their feet

The fossil evidence and rock record also show that the tracksite area represents a lake shoreline environment preserving evidence of a very distinctive 150-million-year-old lake ecosystem. For this reason, the ancient environment has been dubbed "Dinosaur Lake."

The Purgatoire Tracksite, the Picket Wire Canyonlands, and the Comanche National Grasslands are here for our pleasure and education. ***Fossils, trackways, artifacts, and other resources should not be removed or damaged.*** Please keep the area beautiful and complete for our enjoyment today, and for future generations who will visit the area tomorrow.

In the Northern Tract, where the dinosaur tracksite is located, the bottom of the valley floor and the lower portions of the canyon walls are composed of the Jurassic Morrison Formation. The upper portion of the canyon walls is composed of rocks of the Purgatoire and Dakota Formations. The Purgatoire consists of two subunits called the Lytle and Glencairn Members. The lowest prominent cliff in the canyon wall is represented by sandstones of the light buff-colored Lytle Member of the Purgatoire Formation. Blocks of Lytle Sandstone slump down the slopes, often obscuring the base of the formation. The Morrison Formation and the Lytle Member of the Purgatoire Formation are nonmarine deposits that yield terrestrial plant fossils, dinosaur bones and tracks, and fresh water invertebrates such as snails and clams. The Glencairn Member consists of marine shale and forms the greyish-colored slope between the Lytle Member and the overlying, orange-brown Dakota Sandstone Formation that form the cliffs at the top of the canyon.

THE MORRISON FORMATION—THE DINOSAUR "HOLLYWOOD BOULEVARD"

The Purgatoire Tracksite is associated with strata (layers of rock) known as the Morrison Formation. This geologic strata, dating from the Late Jurassic Epoch—about 150-million years ago—is one of the most famous dinosaur-bearing deposits in the world, containing well-known fossil sites such as Dinosaur National Monument. First discovered in 1877, near Morrison, Colorado, the formation quickly yielded some of the world's best known dinosaurs (such as *Stegosaurus* and *Apatosaurus*—better known as "Brontosaurus") in the form of partial or complete skeletons used to stock the world's museums and introduce dinosaurs to a broad international audience.

The Morrison Formation is divided into two members. The lower half consists of rocks deposited in lakes (lacustrine deposits) and the upper half comprises those deposited by rivers (fluvial deposits). The Morrison Formation consists of shales and sandstones that represent floodplain environments and river channels; siltstones and shales that represent soil-forming environments; and limestone layers that represent lake or lacustrine environments. In addition to containing the longest dinosaur trackway known in North America, the Morrison Formation has also produced dinosaur bones, both near and within the Purgatoire Tracksite area. A partial hind limb and foot of a sauropod has been found at the main track site. In 1992, Jim Herrell of La Junta and his brother, Kim Herrell of Castle Rock reported brontosaur bone fossils in the Morrison Formation near the tracksite on private land. In addition, the Morrison Formation yields fish scale, invertebrate, and plant fossils.

PALEOENVIRONMENT

All the sedimentary rock layers of the Morrison Formation that contain tracks at the Purgatoire Tracksite indicate that the depositional environment was a lake basin-hence the name "Dinosaur Lake." The shales clearly represent accumulations of mud in the lake itself when water levels were high, whereas the limestones represent accumulations of coarser, sand-textured sediment along the lake shore when water levels were lower.

The shales contain remains of fossilized algae, snails, and minute crustaceans, all of which are typical of quiet water or low-energy, shallow lakes. By contrast, the limestones contain impressions of large plant stems, scattered fish bones, trampled clams, dinosaur bones, and, of course, abundant tracks. The limestones also contain ripple marks caused by waves and tiny limey spheres known as ooids, which are caused by the action of waves in shallow water. All of this evidence supports the conclusion that the limestones represent limey mudflats around the margins of the lake. The alternation of limestone and shale layers also indicates that the lake level fluctuated from time to time, quite possibly on a seasonal basis, but also on longer-term cycles of decades or centuries. The overall picture is one of a fair-sized lake, several tens of kilometers in diameter (10 kilometers is about 6 miles), with potable water most, if not all of the time. The lake was inhabited by a reasonably healthy flora and fauna of algae, snails, crustaceans, and fish. The lake margins were all or partly vegetated, locally inhabited by clams, and frequented by several different types of dinosaurs.

WHAT DO WE LEARN FROM TRACKS?

Tracks are the evidence of living animals and provide biological insights into the trackmaker's anatomy and behavior. First the tracks tell us: how big the animal was, how many toes it had, if it was a four-footed quadruped or a two-footed biped. These characteristics, along with the age of the strata, usually help us to identify the type of animal that made the tracks. This, however, is just the beginning of the biological evidence that can be gleaned from tracks.

TRACK LAYERS

There are four distinct layers of tracks at the Purgatoire Tracksite, with each layer representing a different episode in prehistory, even though they lie close together. In our initial study, we numbered the layers as beds 1 through 4 (Map Plate 1 on page 15) (Figure 4). Further study reveals, however, that there are three track beds—or levels of track-making episodes—associated with bed 2. This makes a total of six track-bearing levels. What this boils down to is evidence of a minimum of six occasions when dinosaurs visited the lake.

TRACK BED 1

- Abundant evidence of large brontosaurs and various smaller bipedal dinosaurs that trampled through a soft limey mud containing clams and primitive plants known as horsetails. The extensiveness of the trampling indicates that there was a lot of dinosaur activity at this time.

TRACK BED 2—BASAL

- Deep footprints that were made before the limestone accumulated, and were then filled in by bed 2. This suggests that animals were wading in shallow, muddy parts of the lake, perhaps at some distance from the shore.

TRACK BED 2—LOWER TIER

- Contains a few well-preserved tracks of small bipedal, carnivorous dinosaurs that were clearly made before the accumulation of the uppermost layers of this bed. The discovery of tracks within the layer, rather than just on top of it seems to suggest that the sand accumulated along the shoreline more gradually, during a time when dinosaurs walked along the shore. Previous interpretations explained the ripple marks in the bed as deposition by a single storm or flood.

TRACK BED 2—UPPER TIER (NEAR SURFACE)

- Abundant tracks.

TRACK BED 3

- There are a few poorly preserved tracks associated with the top of bed 3. These are in a limestone layer containing fish remains and traces of plant roots.

TRACK BED 4

- The uppermost level of tracks to date. This bed contains the remains of a sauropod skeleton that was damaged and disturbed by extensive trampling activity. The trampling activity was so intense, there are only a few clear tracks. Again, the trampling evidence suggests abundant dinosaur activity in the area.

Overall, the track evidence exhibited at these six different levels indicates that Dinosaur Lake was visited by dinosaurs repeatedly, and that on at least three occasions dinosaurs were probably present in large numbers.

THE TRACKMAKERS

The tracks at the Purgatoire Tracksite fall into only two broad categories. First, there are the large, slightly elephantine tracks of quadrupeds (four-legged) that were undoubtedly made by sauropods (brontosaurs)(Figure 5), and second, there is a variety of three-toed tracks attributable to bipedal (two-legged)(Figure 5) dinosaurs. Tracks are given names by the general type of dinosaur that made them, for example *Brontopodus* for brontosaur tracks.

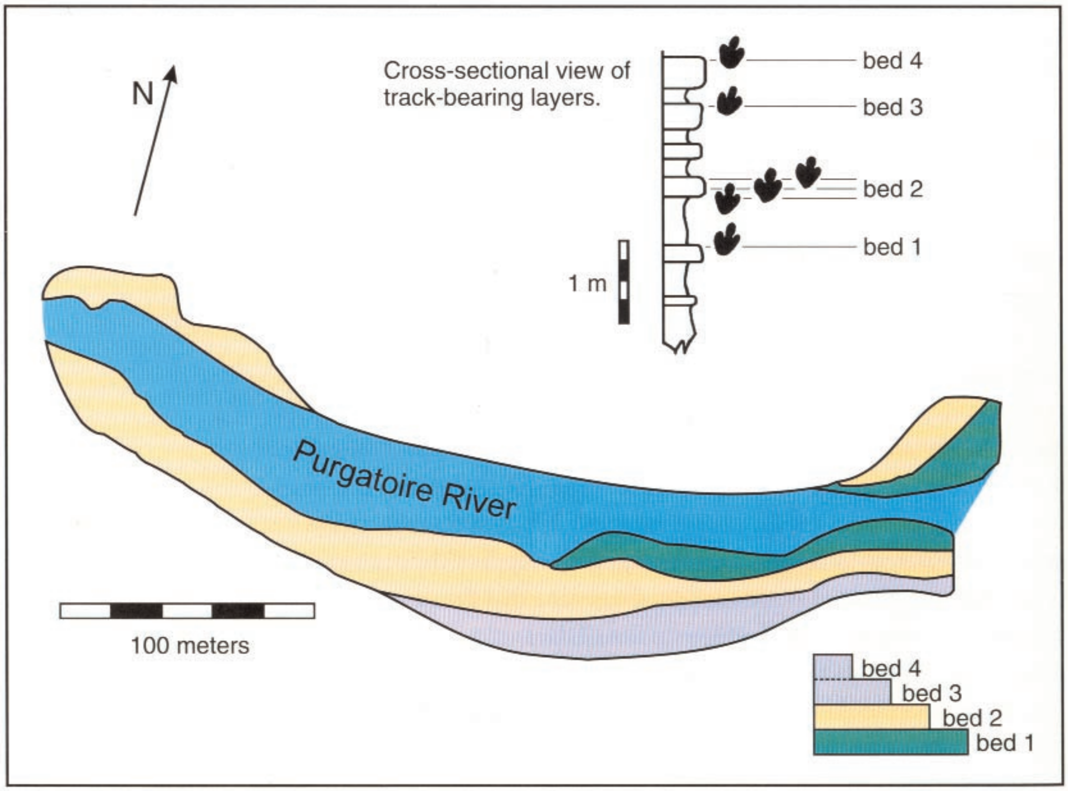


Figure 4. Diagram showing the four layers or "events" of dinosaur activity at the Purgatoire site.

Figure 5. Photo on left: a typical sauropod (or brontosaur) track. Photo on right: the track of a carnivorous theropod dinosaur.

BRONTOSAUR TRACKS

Brontosaur trackways comprise two distinct types, wide-gauge and narrow-gauge. Individual footprints from the Purgatoire Tracksite are narrow-gauge and though similar in general shape to the wide-gauge tracks, they make up a different trackway pattern. Therefore, they can be given a different name, in this case, *Parabrontopodus* (meaning towards or similar to Brontopodus). Among the several dozen trackways at the Purgatoire Tracksite, we have identified a relatively large, broad-footed, narrow-gauge trackmaker and a relatively small, narrow-footed, narrow-gauge trackmaker, which we suggest may represent different dinosaur species. Another possibility is that the tracks represent different age groups or different sexes within the same species.

OTHER DINOSAUR TRACKS

All non-brontosaur tracks at the Purgatoire Tracksite represent bipedal animals with three-toed footprints. Such tracks are usually attributed to carnivorous dinosaurs known as theropods or to the group of mainly bipedal herbivores known as ornithopods. Thus, at least two major groups of quadrupedal dinosaurs, the plated stegosaurs and the armored ankylosaurs—both of which are known from skeletal remains in the Morrison Formation—are evidently not represented at the site. In fact, tracks of these two groups are very rare from the Late Jurassic of North America.

The Purgatoire Tracksite is known for a number of different three-toed track types. They range in size from about 15 centimeters (6 inches) to about 45 centimeters (18 inches) in length. Such a range in size indicates a wide variety of trackmakers, from animals the size of a large turkey to a 9-meter (30-foot) allosaur weighing at least a ton. It is fairly easy to estimate the size of a dinosaur from its footprints. The rule of thumb for most bipedal dinosaurs is that the hip height equals about four to five times the foot length. Therefore, the Purgatoire animals ranged from 0.6 to about 2.5 meters (2 to about 8 feet) at the hip. Knowing these size differences does not allow us to identify the trackmaking species precisely, but it does narrow the choices a little. For example, among the carnivorous dinosaurs that existed during Morrison time, *Allosaurus* and *Ceratosaurus* were two of the larger animals, and *Ornitholestes* was one of several diminutive forms.

CARNIVORE OR HERBIVORE?

Because the two main groups of bipedal dinosaurs, the carnivores (or theropods) and the herbivores (or ornithopods) made very similar, three-toed footprints, it can be difficult to distinguish between their tracks. Useful guidelines are:

- Tracks of carnivorous dinosaurs sometimes reveal sharp claw impressions. Their outline (shape) is also less symmetrical than that of ornithopod tracks.
- Tracks of carnivorous dinosaurs are usually greater in length than in width, whereas tracks of ornithopods are generally as long as they are wide.
- Carnivorous dinosaurs tended to take longer steps and made narrower trackways than ornithopods of the same size.
- Tracks of carnivorous dinosaurs are not as toed-in (pigeon-toed) as those of ornithopods in most cases.

Although these general differences are not foolproof criteria for distinguishing trackmakers, they do provide useful guidelines. Based on these criteria we conclude that most, if not all, of the three-toed tracks from the Purgatoire Tracksite were made by theropods. This conclusion is slightly controversial because many feel that the three-toed trackmakers were ornithopods. Also, a dinosaur community with a large number of carnivores appears to be at variance with normal ecological principles.

WHAT ELSE DO TRACKS TELL US?

- Dinosaur Social Behavior—Trackway directions, abundance of tracks. Sauropods moved in groups.
- Dinosaur Speed—Theropods were fast and erect, saourpods were slower. To calculate the speed of a dinosaur using a trackway, measure footprint length and stride (two steps), and using a pocket calculator, multiply the footprint length by four to get an estimate of the hip height. Apply these measurements to the following formula:

$$v = 0.25\ g^{0.5} \times sl^{1.67} \times h^{-1.17}$$

where v=velocity (or speed), g=the acceleration due to gravity (9.8 m/sec^2), sl=stride length, and h=estimated hip height (or four times footprint length). The final result is in meters per second.

Estimates of speed from Purgatoire theropod trackways fall in the range of 6 to 10 kilometers per hour (about 4 to 6 miles per hour), indicating a brisk walk, but not a run. Estimates for the brontosaurs are somewhat slower-ranging from 3 to 6 kilometers per hour (2 to 4 miles per hour). No one has ever found brontosaur trackways that provided estimates much beyond this speed.

- Dinosaur age groups—Inferred from track size.

TRAMPLING

Anyone can recognize a dinosaur trackway when it is clearly impressed on a flat surface. However, trackers have also learned to recognize layers that have been trampled (Figure 6), churned up, or stomped by the activity of numerous animals. Such trampling can be difficult to study scientifically, but it is nevertheless interesting from several viewpoints:

- Tracks of small dinosaurs tend to be better preserved in the trampled layers.
- Sediment in the trampled layers was softer and therefore may represent a different lakeshore environment than the other non-trampled layers.

Figure 6. Trampling of the surface on some layers at Purgatoire is nearly 100 percent.

- Evidence of trampling other plants and animals such as snails, clams, turtles, and crocodiles. The Purgatoire Tracksite provided one of the first fossil examples of trampled clams ever reported. In one area of bed 1, more than two dozen clams, related to the modern genus *Unio*, were trampled and killed by sauropods.

THE STORY OF DINOSAUR LAKE

Episode 1: The Dinosaurs' First Visit to Dinosaur Lake

At this time the lake was becoming more shallow and a fine limey mud was accumulating in the lake. After a long period of relatively high water, clams were established residents near a vegetated shoreline that sprouted small horsetails about as big around as your finger and probably 1.5 meters (4 or 5 feet) tall. The limey mud in the shallows was soft and sticky, but the water was clear and fresh. There was also plenty of oxygen in the water, allowing fish, clams, snails, and crustaceans to thrive.

The lake was inviting to dinosaurs and other vertebrates, for almost certainly they could drink the water. Tracks are found in abundance in these limey sediments and are a sure sign of potable water—in Africa today the abundance and variety of tracks around lakes is a measure of the water quality. Amongst the horsetails and other plants, turkey- and emu-sized theropods left a variety of tracks that even in Jurassic times may have been indistinct and muddled. The smaller animals may have been completely hidden in the vegetation. No doubt the carnivores took advantage of any food sources available, including fish, insects, and trampled clams. Evidence from other sites suggest that frogs and other small vertebrates were common in lake and pond environments.

Brontosaurs were the most abundant herbivores, and their numerous tracks show that they trampled through this limey mud, both in the shallows where the sediment was softer and on the firmer footing above the waterline. They passed by in groups and individually and extensively trampled the vegetation.

Episode 2: Dinosaur Visits Two Through Four

For a few years the shoreline scene shifted away from the place where the Purgatoire flows past Rock Crossing. Water level rose and expanded the lake towards the south. After awhile the lake level dropped again and the shoreline edged back to the area of Rock Crossing. A little muddy limestone accumulated in the shallows not far from the shore, and large dinosaurs waded in, leaving very deep footprints (Visit Two).

Soon conditions changed again along the lakeshore, and a new type of limey sands began to accumulate.As the sand was washed back and forth, it produced even, flat surfaces on which dinosaurs walked both during and after the final accumulation of the layer (Visits Three and Four). Over much of the area the surface was quite firm-too firm to allow small dinosaurs to produce clear tracks—but to the north the tracks get deeper, indicating a wetter substrate. The majority of brontosaurs that crossed the area appear to have been moving west, and on at least one occasion a group of five or more juveniles moved west, leaving perfectly parallel trackways.

All the brontosaurs left narrow-gauge trackways, perhaps indicating that they were all of the same type, although they varied considerably in size. In addition to at least forty of these individuals, about sixty theropods also crossed the area moving in all different directions. In a relatively short period of time, at least a hundred animals crossed a stretch of shoreline of less than one-half kilometer (one-quarter mile) long. No doubt the wave-agitated waters were still suitable to drink despite lower lake levels.

Episode 3: Dinosaur Visits Five and Six

The lake level rose and dropped again—first bringing mud into the area, and then more sandy-textured limestone. This time the sediment contained lots of fish scales, probably indicating that a lot of fish had recently died in the lake, perhaps during the most recent drop in water level or as the result of some other environmental stress. Plants encroached on the lakeshore, sending out horizontal roots—a sign that the water table was still high. A few dinosaurs left indistinct tracks on the firm sediment.

Conditions changed again, but this time more subtly, producing more sandy limestone and an accumulation of fine limey mud rather than shale. This indicates that lake levels did not rise much. At least two dinosaurs (one a brontosaur) came into the area and died. The brontosaur was not ripped apart and scattered by predators or scavengers—at least not to any great degree—for we find most of the hind limb intact. However, many brontosaurs came into the area and trampled these sediments, damaging and disturbing the bones where they lay and obliterating most of the ripple marks and other evidence of the sedimentary history of the layers.

Thus, the track story of Dinosaur Lake ends as it began, with abundant evidence of dinosaur activity along the shores of a living lake.

PUBLIC ACCESS AND OTHER UNRESOLVED ISSUES

The Purgatoire Tracksite is in an isolated area, 23 miles from La Junta (Figure 7). Access is both limited and physically difficult. There are two routes into the area, one through Iron Canyon and another through Withers Canyon. Access by these routes is limited by the terrain, Forest Service closures, and Army administrative polices. The Iron Canyon route crosses the Army's Pinon Canyon Maneuver Site and access is through locked gates by permission only. Because the Army has absolute priority in using the Pinon Canyon Maneuver Site, guided auto tours are difficult because they must be booked

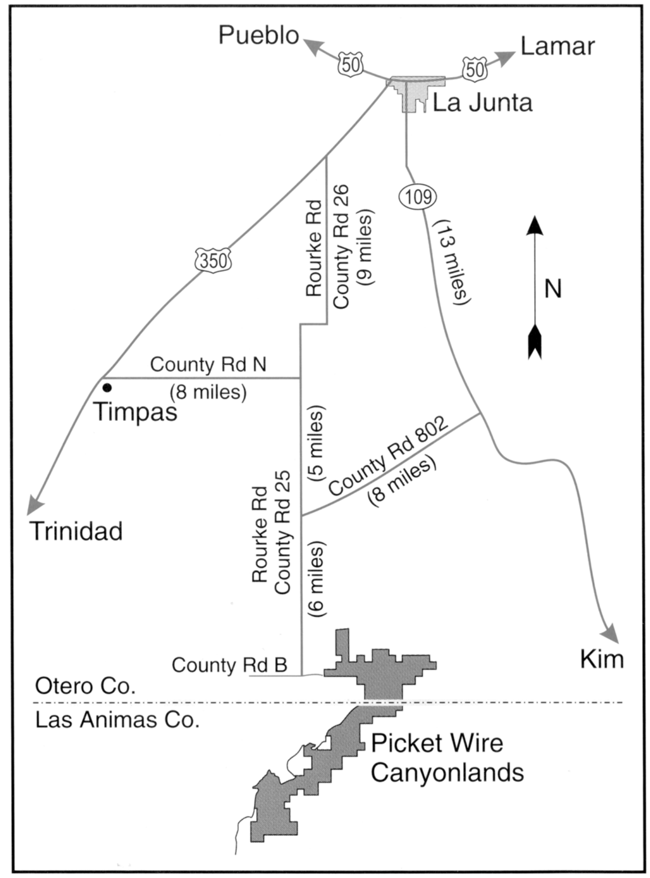


Figure 7. Road directions to the Picket Wire Canyonlands.

months in advance and may be cancelled at the last moment if the Army schedules a maneuver. In addition, this tour requires a four-wheel-drive vehicle and a Forest Service guide, also subject to availability.

To overcome this limitation and accommodate the public's desire to view the dinosaur tracksite, rock art, and other heritage resources, the Forest Service has established a second access to the area through Withers Canyon that is open daily (Figure 8). Withers Canyon is the only allowable access to the Canyonlands for the general public, and access is allowed only by foot, mountain bike, or horseback at the present time. This access is quite lengthy—10.6 miles roundtrip from the head of Withers

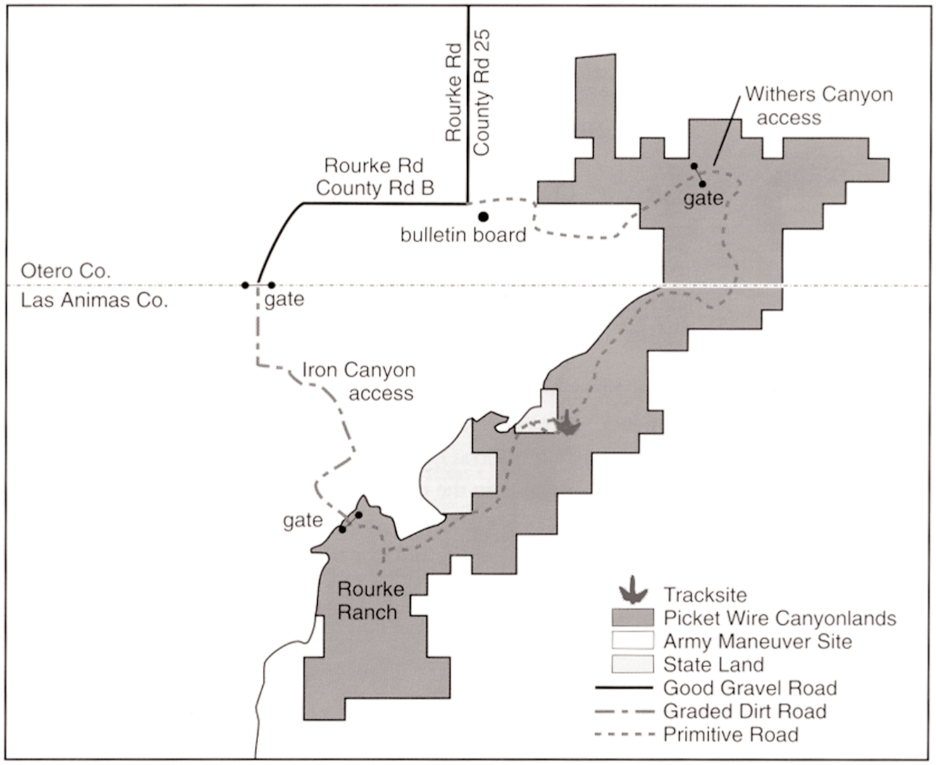


Figure 8. Access routes into the Picket Wire Canyonlands.

Canyon to the tracksite. The length of the hike can increase to 16.6 miles roundtrip from the bulletin board to the tracksite, depending on the road conditions from Withers to the bulletin board. Although the trail follows a dirt road it is rough in places, changes in elevation about 500 feet, is not well marked, and can be hazardous in a thunderstorm when the roads and trails become muddy and flashfloods occur. During the summer, heat, lack of drinkable water, and the presence of rattlesnakes make this hike hazardous. This access is not suitable for school groups, the disabled, or anyone in poor physical condition.

The current access situation precludes many people from visiting the dinosaur tracksite. Buses and low-clearance vehicles cannot safely negotiate the roads; there are no facilities or trails for the physically challenged; and reservations for guided auto tours must be booked months in advance. The long hike prevents many visitors, particularly children and the elderly, from enjoying the tracksite.

It is important to remember to have as little an impact as possible while visiting the paleontological, archaeological, and historical sites of the area. We want you to enjoy these wonderful resources—as much and as often as you like—but we would also like your children and grandchildren to enjoy them just as much. If you are able to visit the tracksite, please do not take anything other than photos, and do not make casts of the dinosaur tracks, or rubbings or otherwise touch the rock art or other artifacts you may see.

USEFUL REFERENCES

There are many references to the Purgatoire Tracksite. Some comprise articles and reports that include a few illustrations and short summaries of features seen at the site. There are also many technical articles on the geology of southeastern Colorado. We have included only those articles and books which provide the most pertinent background information on the site, and the geology, paleontology, and archaeology of the area. Additional references can be found in these articles.

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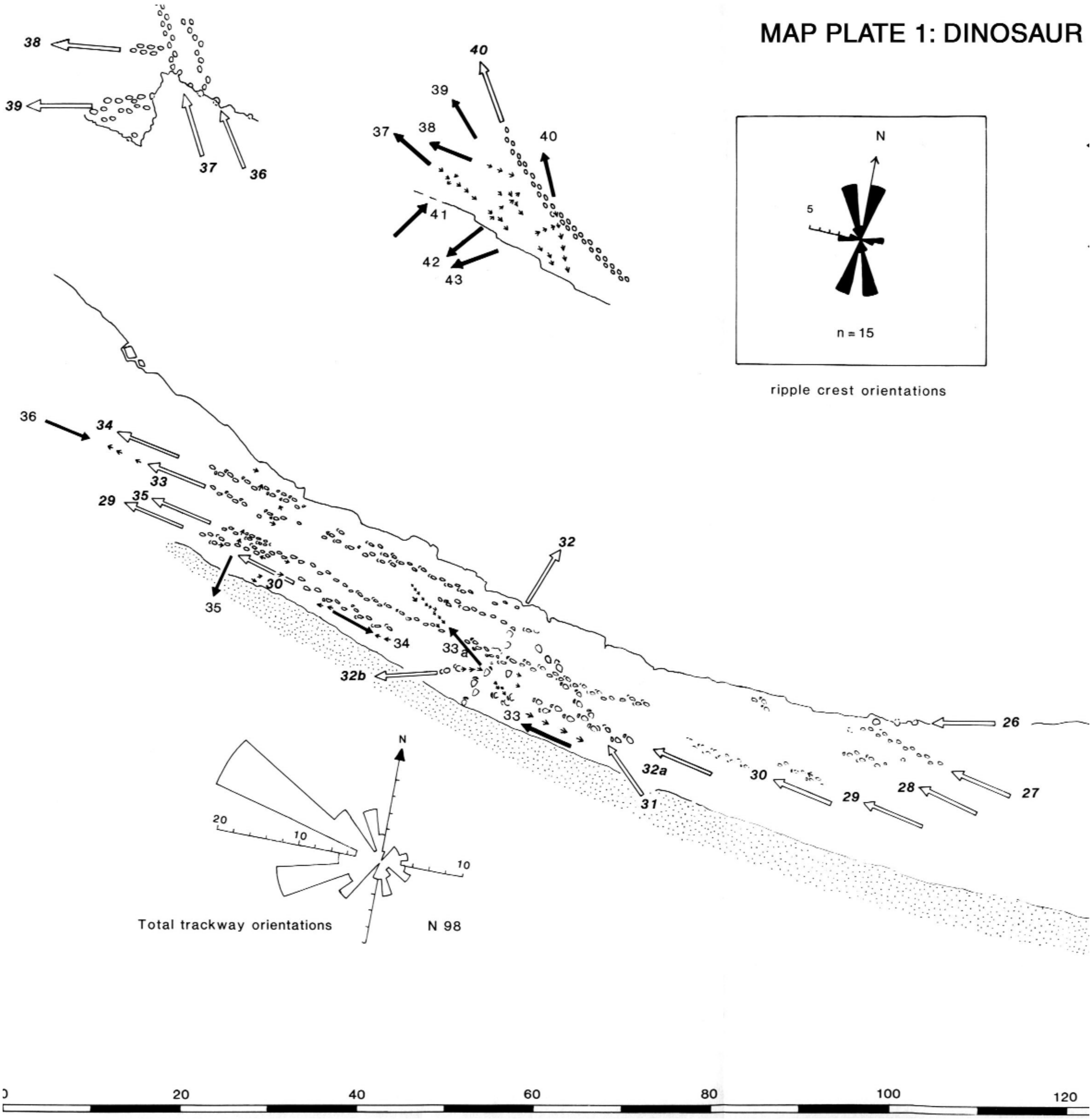
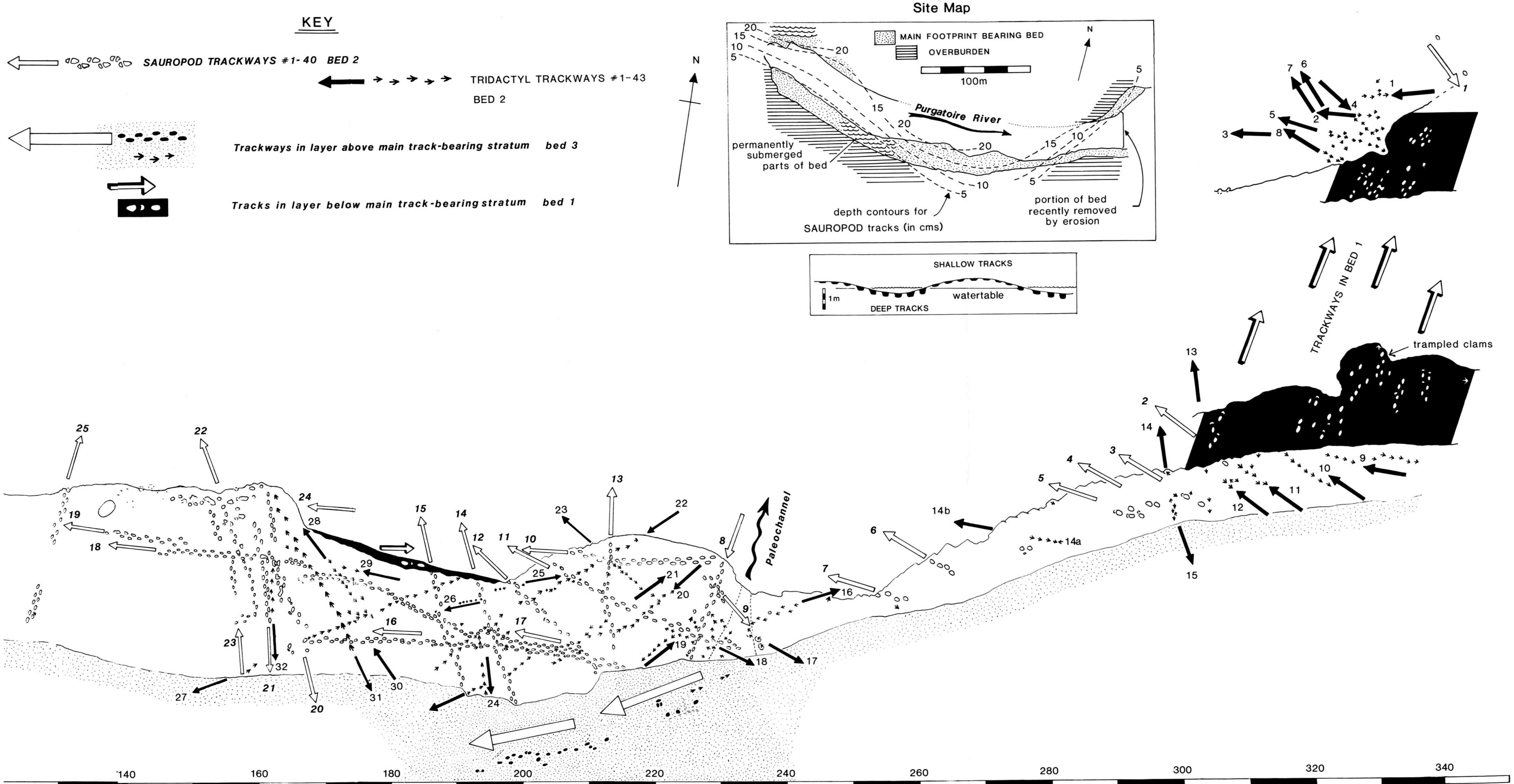
MAP PLATE 1: DINOSAUR



FOOTPRINTS IN THE MORRISON FORMATION, PURGATOIRE RIVER SITE, SE COLORADO



from Lockley et al., 1997

The K/T Boundary Impact Layer of Southern Colorado and Its Relation to the Chicxulub Crater, Mexico

By Matthew L. Morgan
Colorado Geological Survey

INTRODUCTION

Sixty-five million years ago a spectacular event occurred over what is now the Yucatan Peninsula of Mexico. An asteroid or comet slightly smaller than the size of Denver (~10 km), traveling at roughly 30 km/sec, slammed into the earth leaving a crater more than 150 km in diameter (Figure 1). The crater is now officially called Chicxulub (pronounced cheek-shoe-loob). Giant tsunamis over a kilometer high swept across the Yucatan Peninsula and the Gulf Coast causing massive destruction on land and triggering submarine landslides in the ocean (Alvarez, 1997). The ejecta, composed of pulverized and melted rock resulting from the impact, was launched like a bullet into and beyond the earth's atmosphere. Some material came to rest around the circumference of the crater, forming an ejecta blanket hundreds of kilometers wide. The remaining material circled the globe and blocked sunlight, turning day into night. All was not over. As the ejecta rained down, friction heated the debris turning the atmosphere into an oven, baking the ground and everything on it and igniting the vegetation and forests. Soot from the fires added to the ejecta cloud that

Figure 1. Location of the Chicxulub crater with the Colorado state boundary for perspective. The buried 180-km diameter (111 miles) crater is located on the shelf of the Yucatan Peninsula of Mexico.

shrouded the earth (Alvarez, 1997). The surface of the earth was changed in an instant. Mammals took the place of the dinosaurs.

THE SMOKING GUN

Evidence of this great impact is seen in deposits around the world. Core samples drilled into the ocean floor off the eastern coast of Mexico revealed breccia and suevite (pronounced sway-vite), a form of impact-melted rock, caused by the collision of the impacting body (Figure 2).

Hundreds of other core samples taken from the Gulf of Mexico and the Caribbean revealed the same. Outcrops in Texas, New Mexico, Wyoming, and Colorado also retained the remnants of the impact in the form of shocked minerals and tektites, small droplets of melted rock turned to glass that fell to earth following the impact (Figure 3).

Controversy still surrounds the tektites. In 1990, Glen Izett of the U.S. Geological Survey, studied the K/T boundary locations of southern Colorado and northern New Mexico. Izett noted that the microscopic texture of the tektites did not resemble that of altered glass. He also cited the presence of carbonaceous plant material within some of the tektites, strongly refuting their impact origin (Izett, 1990). However, it is important to note that both impact glass and ejecta spherules have been conclusively identified at several K/T boundary sites surrounding

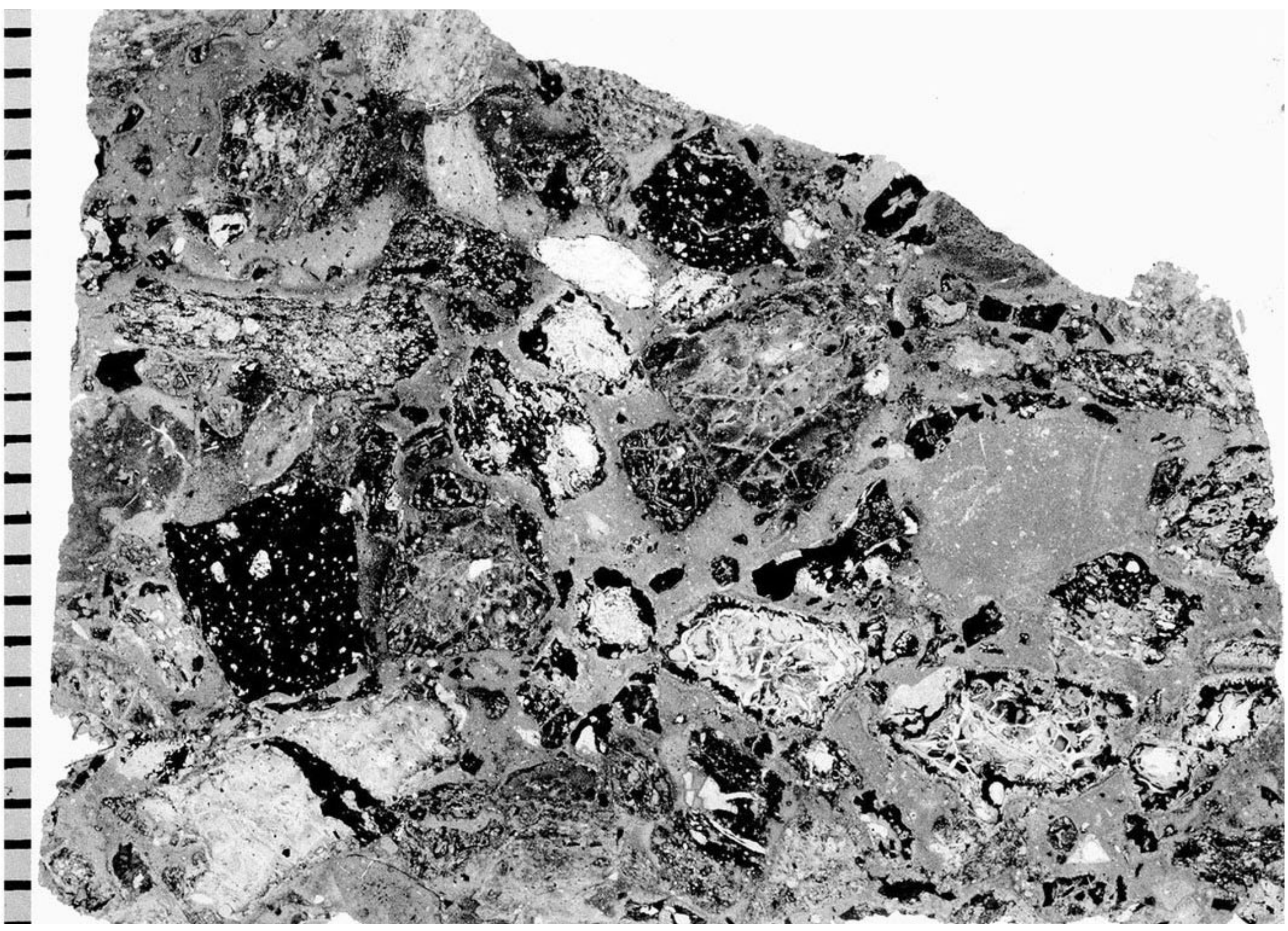


Figure 2. Suevite from the Chicxulub crater. The suevite is composed of carbonate (white clasts) and basement rock (dark clasts) set in a frothy matrix of calcite, feldspar, and quartz. Scale on left is in millimeters. Photo courtesy of Philippe Claeys, Inst. Mineralogie Berlin.

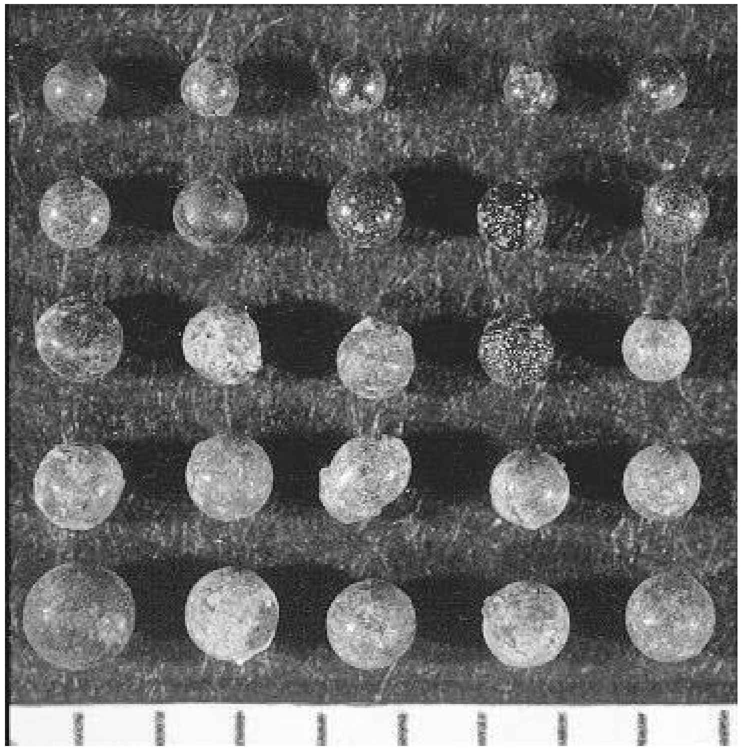


Figure 3. Possible ejecta spherules recovered from a K/T boundary outcrop near Dogie Creek, Wyoming. The glass of the spherules has been completely altered to clay. Scale is in mm. Photo courtesy of Alan Hildebrand.

the Gulf of Mexico. At these locations, the spherules and glass are associated with massive tsunami deposits, the result of large waves created by the impact (Claeys, 2000).

The search for the crater began in the mid-1970s. Geologists were puzzled over a thin layer of clay located near the small town Gubbio, Italy which was dated to be the boundary between the Cretaceous and Tertiary Epochs (K/T boundary)(Alvarez, 1997). The fossilized organisms in the rocks greatly decreased in number and complexity above the clay layer (Figure 4). While the extinction of the dinosaurs is synonymous with the K/T boundary, other organisms such as small mammals and plants suffered as well.

In 1977, the clay was found to contain anomalously high amounts of iridium, an element commonly found in meteorites (Figure 5). The same clay layer was discovered at dozens of other locations around the world including several good exposures in southern Colorado. In 1991, through years of collaborative efforts between dozens of scientists who studied the K/T boundary locations and other impact craters, the Chicxulub impact site was found buried beneath the Yucatan Peninsula of Mexico (Figure 6) (Alvarez, 1997). The crater was the right age and size for creating the widespread deposits.

COLORADO LOCATIONS

Southern Colorado and northern New Mexico is host to over 17 K/T boundary sites (Figure 7) (Izett, 1990). It is in these outcrops that the original iridium-rich clay layer is preserved. The

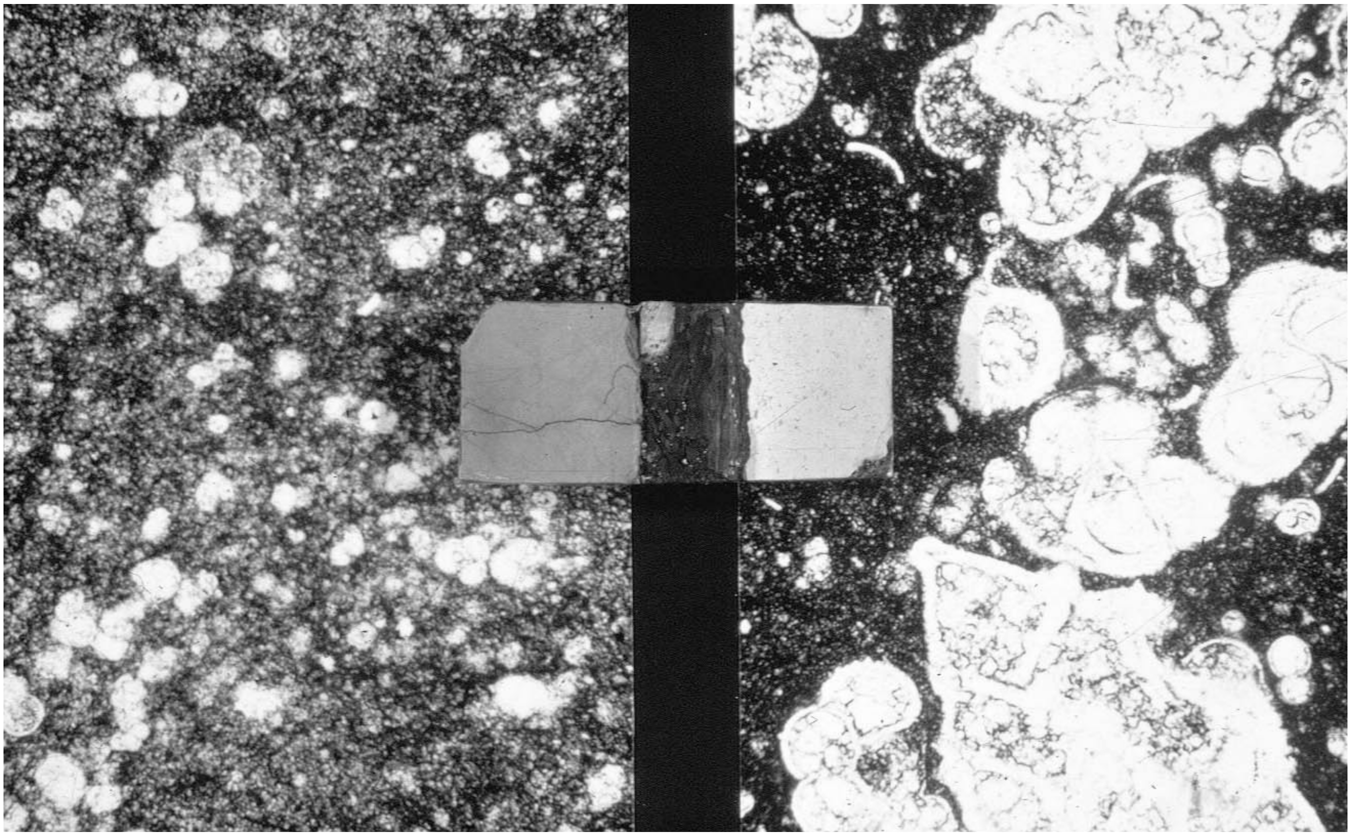


Figure 4. Image showing the distinct faunal change that took place over the K/T boundary (center of image). On the right (late Cretaceous), foraminifera are abundant and healthy, however on the left (early Tertiary) the foraminifera are sparse and growth is stunted. Image courtesy of A. Montanari.

ejecta cloud composed of shocked mineral grains, ejecta spherules, and rock fragments, blanketed the earth and settled to the surface. This blanket was preserved only where conditions were perfect. During Cretaceous time (65-144 Ma), central Colorado was the shore of the Cretaceous Epiric Seaway, an inland body of water extending from northern Canada to the Gulf of Mexico. The shoreline looked similar to present-day Louisiana, with deltas, mudflats and swamps. The K/T boundary clay was preserved in the calm, non-agitated waters of the swamps where it was not affected by erosional processes such as wind and rain. The swamps later became the rich coal deposits of the Raton Basin.

The boundary clay in Colorado is seen as a thin, less than 1 cm thick layer of creamy-white kaolinitic clay sandwiched between layers of organic-rich coal and carbonaceous shale (Figure 8) (Pillmore, 1987).

Shock-metamorphosed minerals such as quartz, plagioclase, and microcline are found in the top 2-3 mm of the bed. These minerals display microscopic planar deformation features (PDFs), caused by shock waves passing through rocks of the Yucatan Peninsula during and preceding the impact event. PDF's are now widely accepted as criteria for impact origin (Figure 9).

Chemical analysis of the boundary clays in Colorado shows an iridium anomaly with concentrations reaching 13.5 parts-per-billion or 8000x background levels (Pillmore, 1987). Levels of this magnitude are measured at dozens of other K/T boundary locations worldwide.

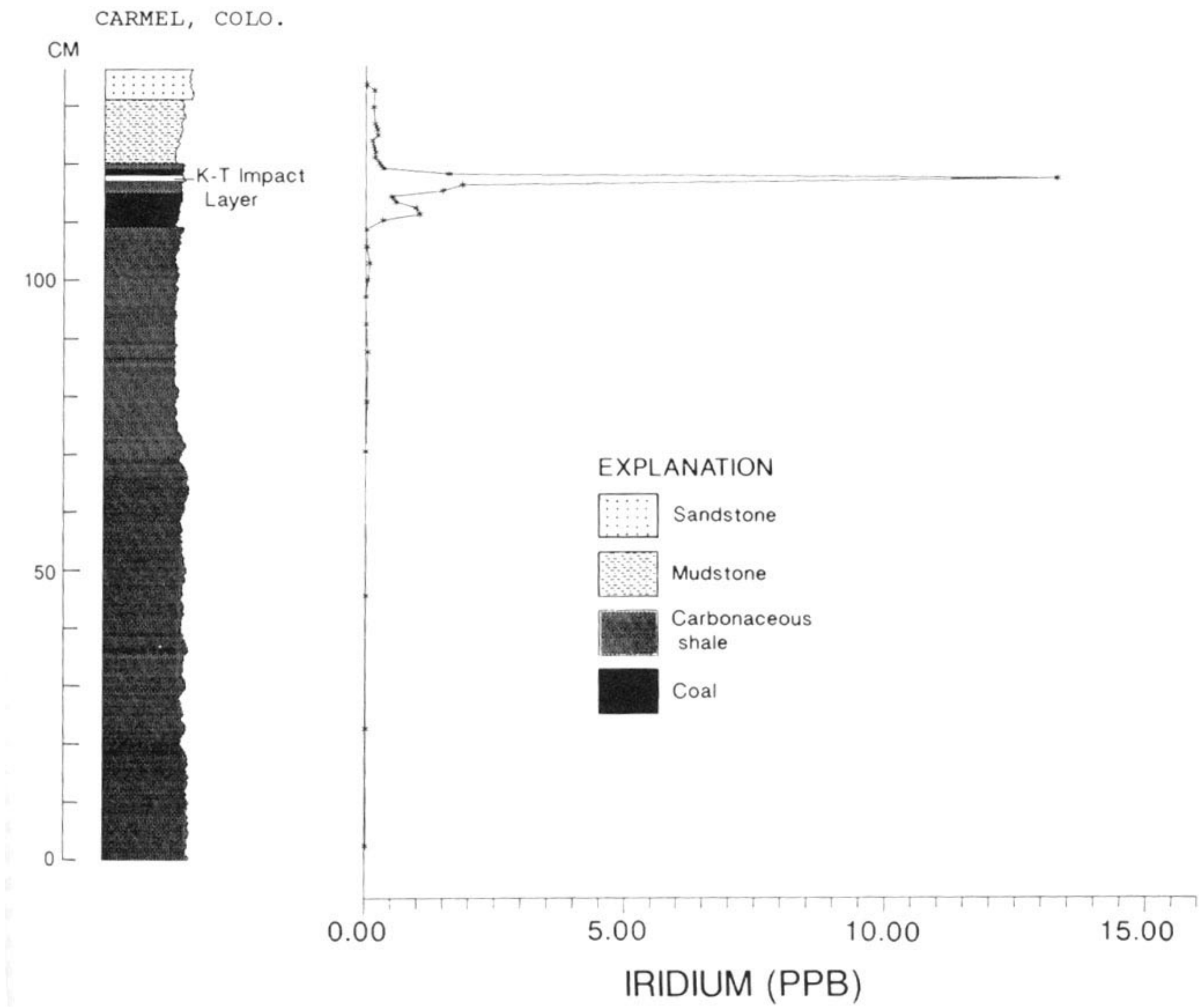


Figure 5. Iridium concentration of the Carmel, Colorado K/T boundary clay location. From Izett, 1990.

Even though the Raton Basin of Colorado is over 1500 miles from the point of impact, the original impact materials and anomalous chemical signatures are still preserved. The importance of the boundary clays in Colorado and other localities helped scientists locate the Chicxulub crater and eventually piece together the events surrounding the K/T impact event. The impact changed the planet forever, ending the time of the dinosaurs and beginning the reign of the mammals.

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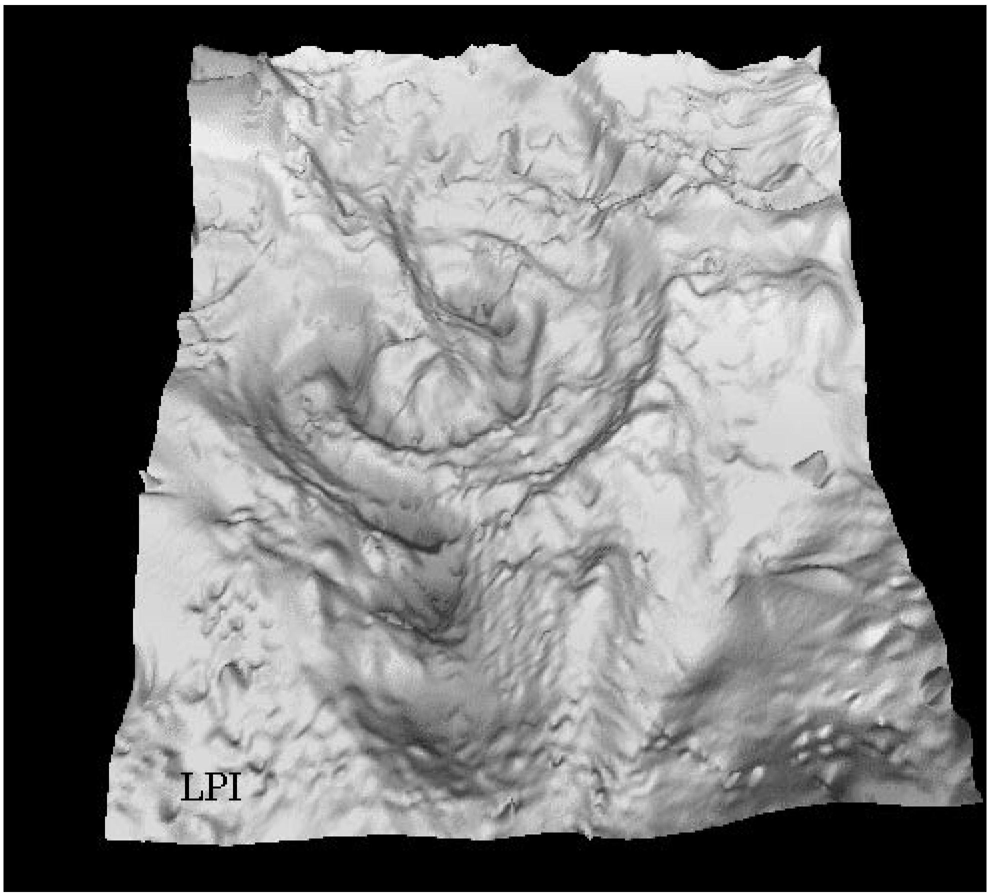

Figure 6. Bouger gravity map of the Chicxulub crater. The crater's circular shape is easily visible. Image courtesy of V. B. Sharpton, Lunar and Planetary Institute, NASA.

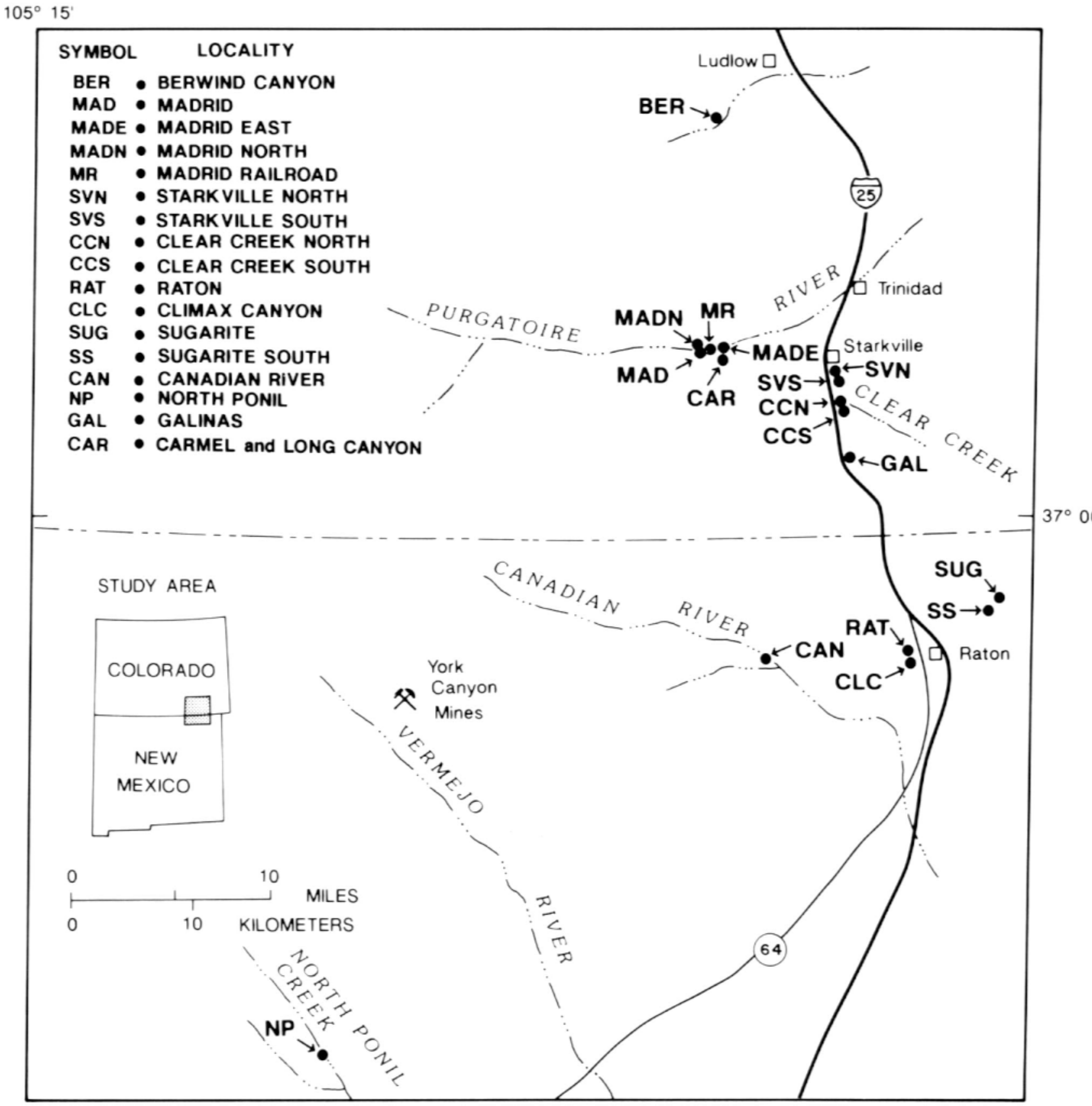

Figure 7. K/T boundary clay locations of the Raton Basin, Colorado and New Mexico (from Izett, 1990).

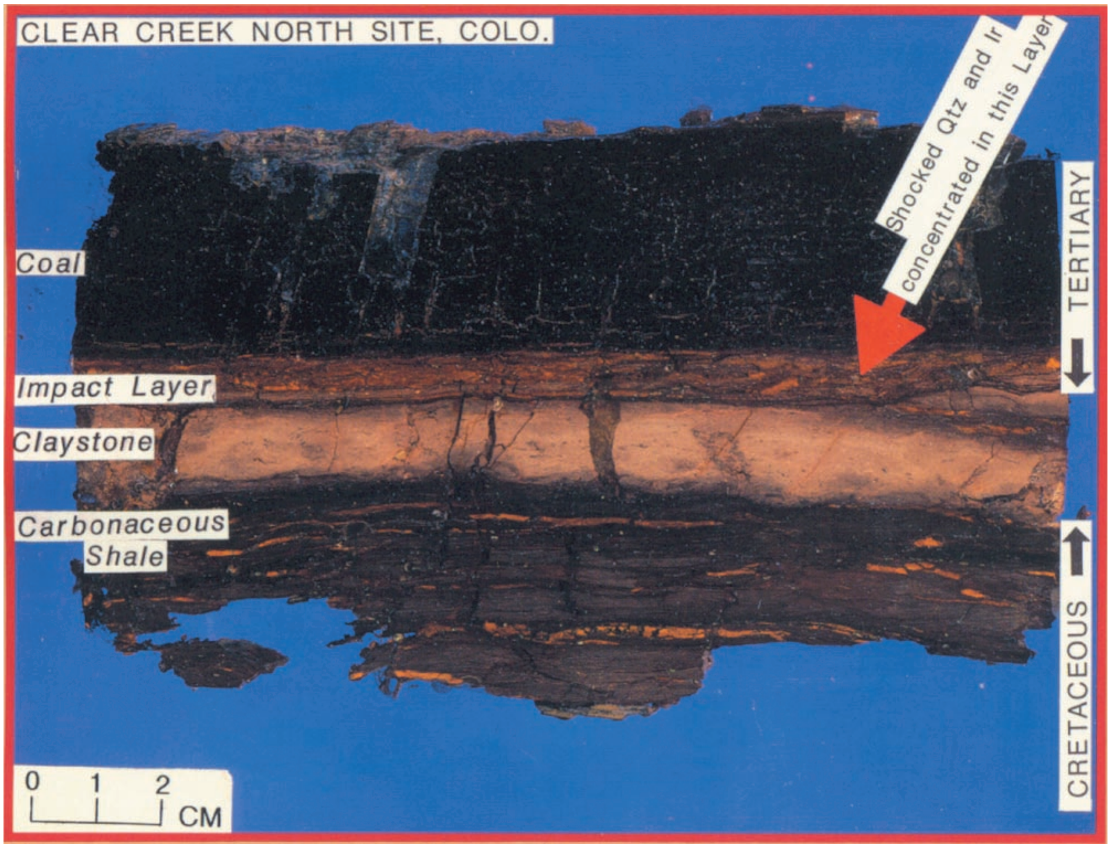

Figure 8. Annotated section of the K/T boundary clay and surrounding beds from the Clear Creek North, Colorado location (from Izett, 1990)

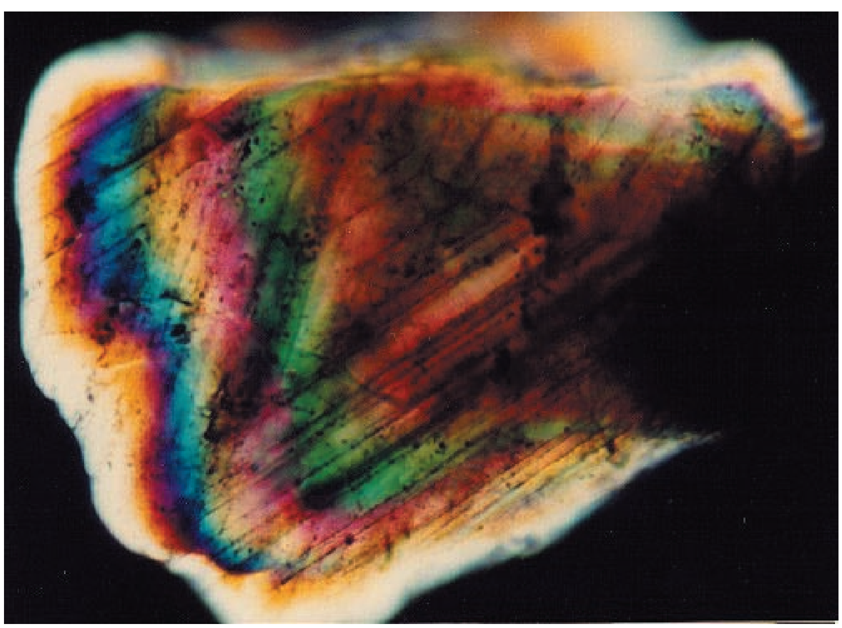

Figure 9. Shocked quartz from the K/T boundary. The parallel lamellae, called planar deformation features (PDF's) are formed from extreme pressures at the time of impact.