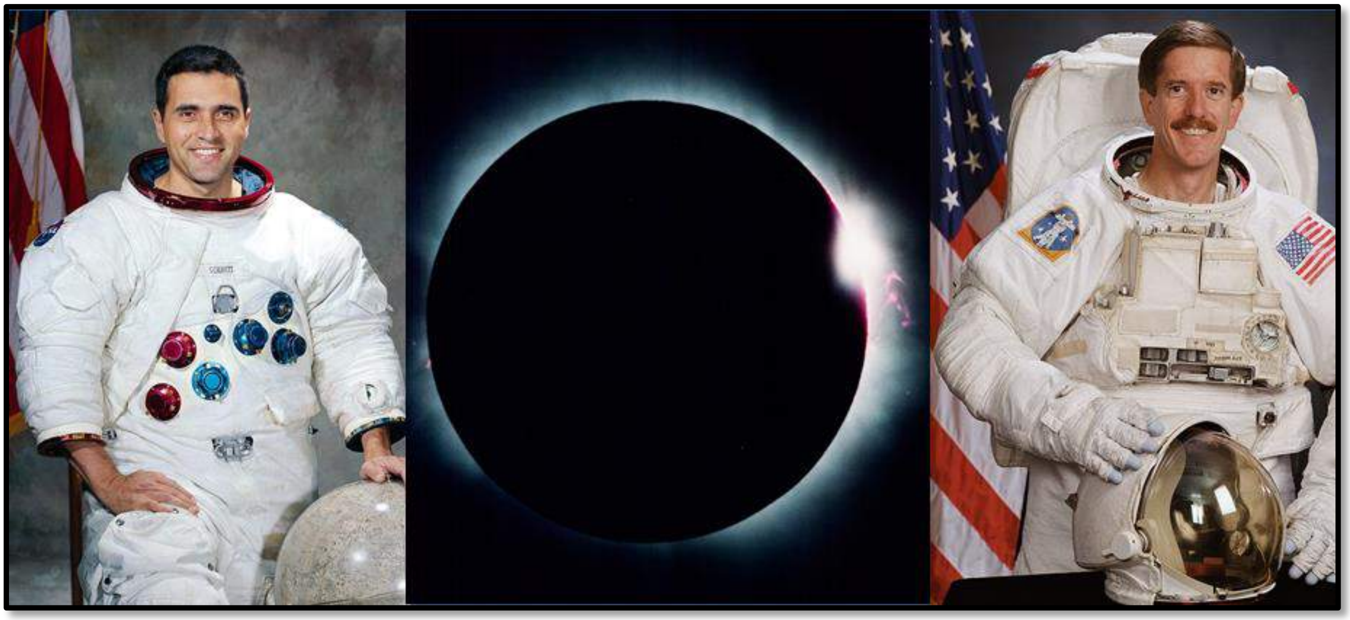
# AAPG TOTAL SOLAR ECLIPSE SEMINAR

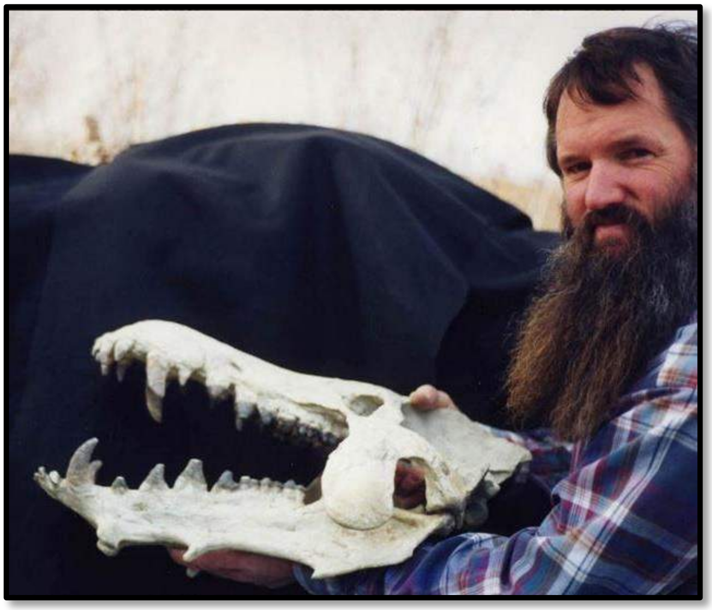
# FIELD GUIDE

to:
Impact Craters and Outcrops of the K-T Boundary

## Casper, Wyoming USA

### August 18-22, 2017





**Published July 28, 2017**

## AAPG TOTAL SOLAR ECLIPSE SEMINAR

# FIELD GUIDE

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# ACKNOWLEDGEMENTS

This Field Guide was compiled by Doug Cook who accepts all responsibility for mistakes, errors, and omissions. Kent Sundell compiled the field logs.

Special thanks to Jack Schmitt and Jim Reilly whose tireless participation and enthusiasm in AAPG Astrogeology events give us their professional perspective and expertise.

We owe mountains of gratitude to Kent Sundell, Casper College, staff and students for organizing, guiding, and operating the field trips in this Seminar.

Thanks to Don Clarke whose eclipse experience, ideas, and Casper connections were the catalyst for the AAPG Eclipse Seminar.

Thanks to Karl Osvald for his contribution of knowledge on Wyoming astrogeology at the Douglas impact site and Linch/Sussex K/T Boundary sites.

Thanks to Susan Nash, Alicia Collins, and Stephanie Brown at AAPG and Anna Wilcox at Eclipse Casper whose background organizational efforts made this event possible.

## AAPG TOTAL SOLAR ECLIPSE FIELD SEMINAR
## August 18-22, 2017

**La Quinta Inn Casper**
400 W F St, Casper, WY 82601
(307) 265-1200

## ITINERARY

**August 18.** General Arrivals La Quinta Hotel check-in. Contact Doug Cook for arrival detail questions: 719-208-5510.

**Meet and Greet** 5 PM La Quinta Sky Vue Room
**Icebreaker Dinner** 6 PM *The Fort Restaurant* next to La Quinta

**Evening activity:** 7-9 PM La Quinta Sky Vue Room Presentation / Orientation / Basic astronomy. Distribute Guide books. Eclipse glasses/filters. Safety briefing.

**Doug Cook** Field Astrogeology presentation.

**Dr. Kent Sundell** Field Paleontology presentation.

Telescope to be set up near hotel for a look at Jupiter and Saturn.

**August 19**.
Breakfast at hotel. Convene in Sky Vue Room.
8 AM Vans depart La Quinta front parking lot.

**Field Day Trip** to Linch, Wyoming to visit an early recorded and well located K/T boundary site having almost all classic features carbon, clay, shocked quartz, fern spike above, and dinosaur bones below. On the way to Linch boundary site we can stop at a newly discovered Cretaceous dinosaur quarry with various remains of *Triceratops*, *Ankylosaurus*, and *T. rex*. and help dig or search for your own dinosaur bones in the Lance Formation. We will also pass through the famous Salt Creek and Teapot Dome oil fields having produced more than 1 billion barrels of oil from the western margin of the Powder River Basin, which is one of the largest energy production regions of the United States. Resources include: Coal, oil, gas, coal bed methane, horizontal drilling and fracking of shales and tight/thin sands, U.S largest uranium resources, and numerous wind farms; Box lunch; Return to La Quinta by 4:30 PM.

**August 19 Evening**: Catered dinner at *Casper Country Club*.
4149 Country Club Road.

6 PM Welcome reception. 7-9 PM Dinner. Astronaut-geologist presentations-

- **Jack Schmitt** *Apollo 17: 45 Years and Counting*.
- **Jim Reilly** *Martian Diners and Dives: Mark Whatney Should have had Fish and Chips!*

**August 20**.
Breakfast at hotel. Convene in Sky Vue Room.
8 AM Vans depart La Quinta front parking lot.

**Field Day Trip** to Douglas, Wyoming (45 minutes from Casper) to visit a series of five small impact “exhumed” impact craters within the Pennsylvanian Casper Formation. These features have never been studied in detail and could provide a lively discussion in the field as to timing, size and speed of impactor. After lunch we will visit nearby scenic badlands featured in numerous paleontology films (Walking with Prehistoric Beasts-BBC, Razor Jaws-Nat Geo, Killer Pigs-Nat Geo, Dawn of the Cats-Paleoworld, Valley of the Uglies-Paleoworld) and be allowed to collect Oligocene and late Eocene vertebrate fossils, possibly including saber tooth cats, *Archaeotherium*-killer pig, Hyaenodon-razor jaws, oreodonts, camels, horses, rhinos, deer, rabbits, rodents, insectivores, marsupials, snakes, lizards, and large land tortoises (some > 200 pounds). Dr. Sundell has studied this badlands area for more than 40 years and collected more than 5,000 skulls and skeletons; Box lunch. Return to La Quinta by 4:30 PM.

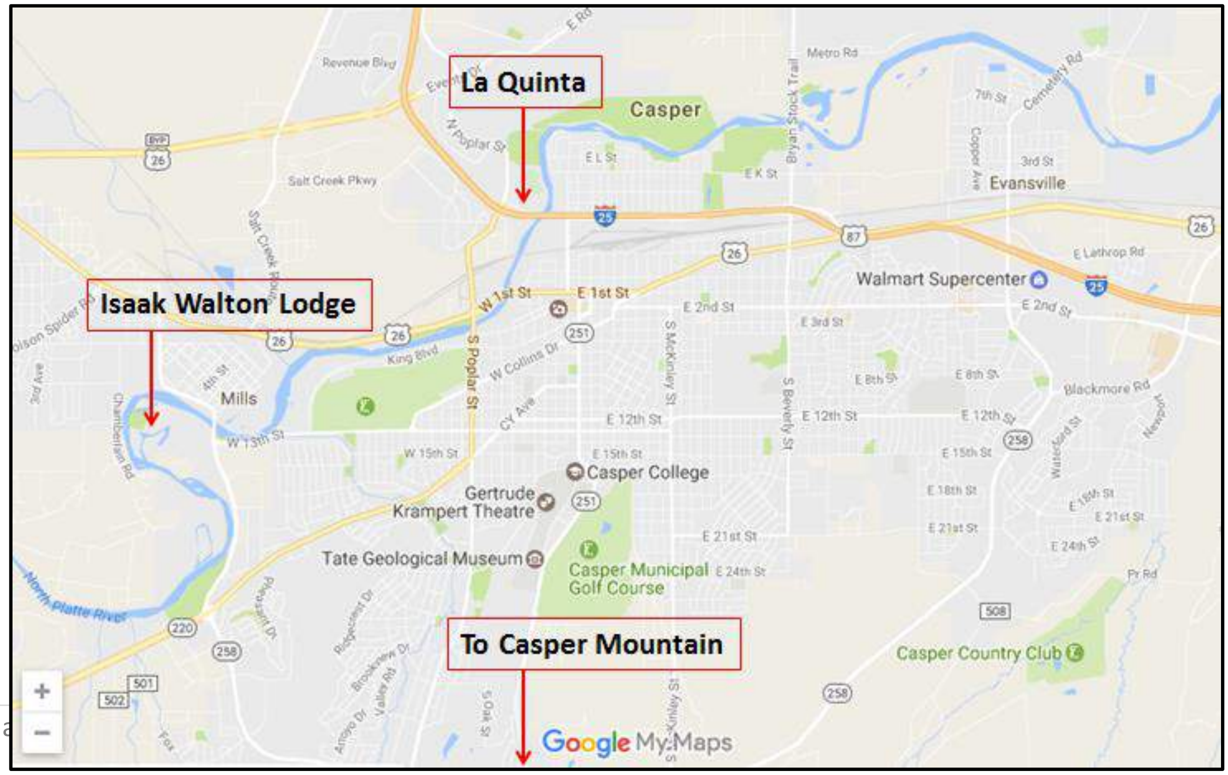
5-7 PM. Dinner at your leisure. Reservations recommended. Carpooling or vans can be arranged.
**Evening activity:** 7-9 PM La Quinta Sky Vue Room. Presentation. Eclipse astrophotography briefing; Star gazing (weather permitting). Primary site: W. Casper; Hwy WY 257 42°48'53.23" N 106°27'8.67"W.

**August 21**.
Breakfast at hotel. Convene in Sky Vue Room.
8 AM Vans depart La Quinta front parking lot.

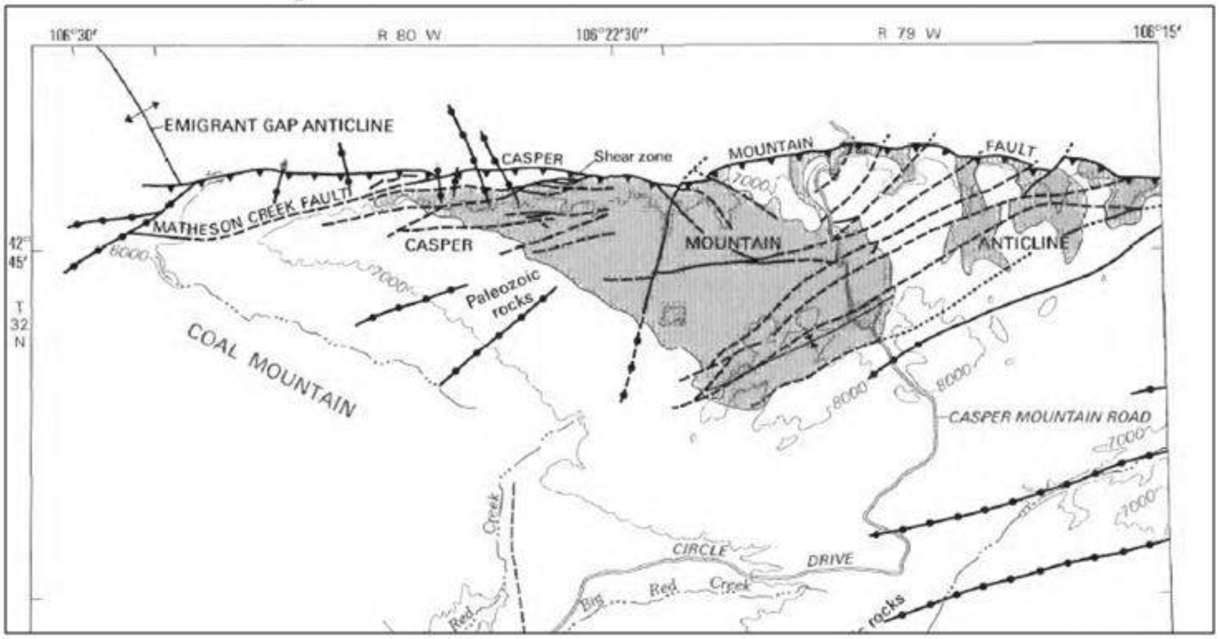
**Total Eclipse! Isaac Walton Lodge venue.** Ft. Caspar Rd., Casper, WY, 42°50'19.59"N 106°22'26.83"W. Equipment set-up, view, and photograph the eclipse; Lunch and dinner: picnic and BBQ at the Lodge.

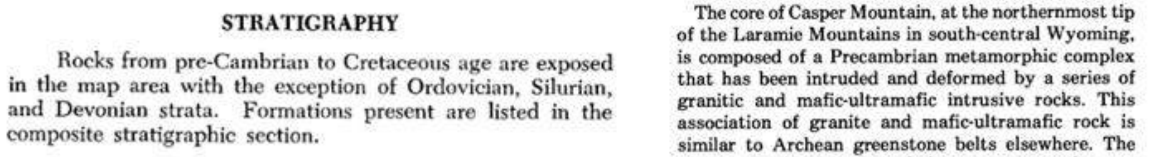
**Evening**- Share eclipse photos/stories. Star gazing. Vans staggered return to hotel by request.

**August 22**.
Breakfast at hotel. Convene in Sky Vue Room. Check-out by 12 Noon.
Departures on your schedule.
**AIRPORT TRASFERS CAN BE ARRANGED with your request and flight details.**



# Casper Mountain Structure

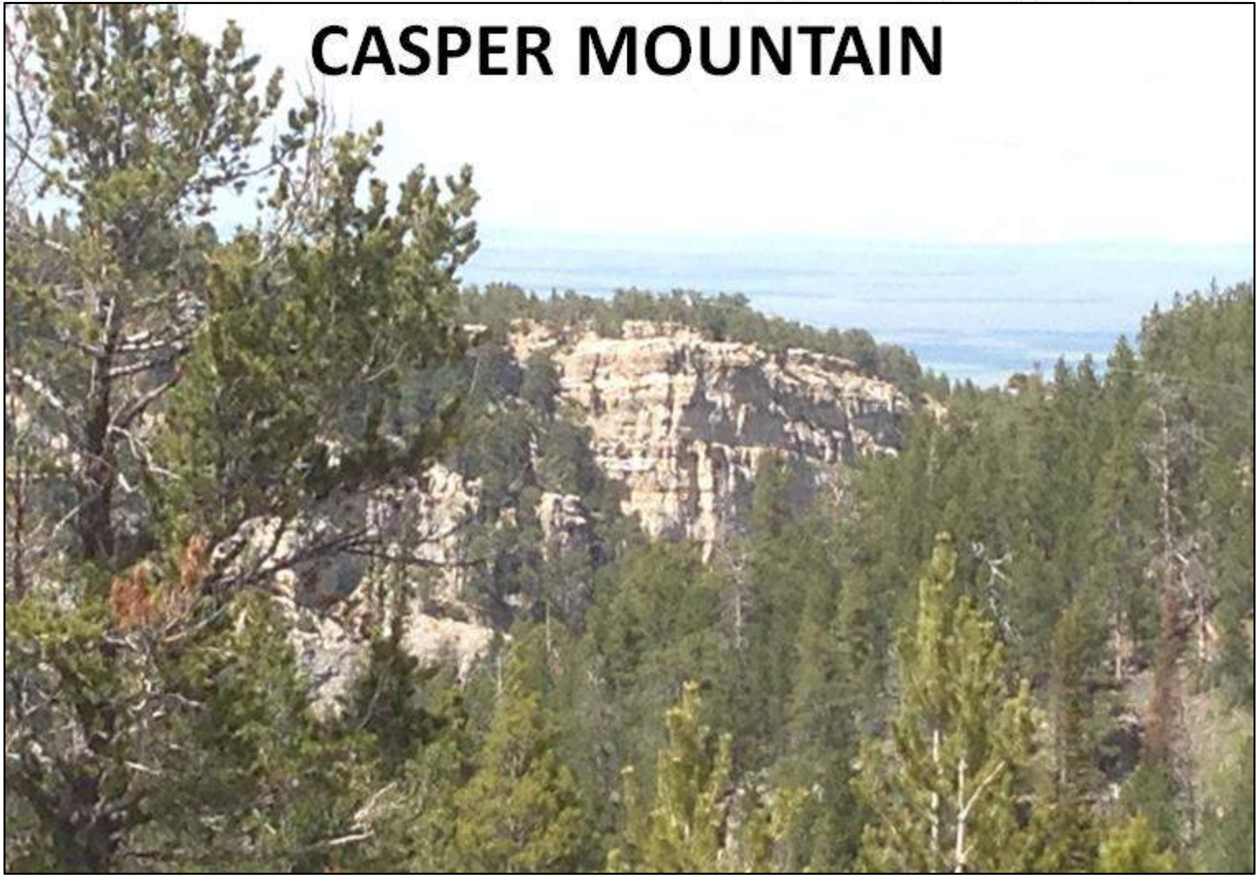




**STRATIGRAPHY**

Rocks from pre-Cambrian to Cretaceous age are exposed in the map area with the exception of Ordovician, Silurian, and Devonian strata. Formations present are listed in the composite stratigraphic section.

The core of Casper Mountain, at the northernmost tip of the Laramie Mountains in south-central Wyoming, is composed of a Precambrian metamorphic complex that has been intruded and deformed by a series of granitic and mafic-ultramafic intrusive rocks. This association of granite and mafic-ultramafic rock is similar to Archean greenstone belts elsewhere. The



# INSTRUCTORS

**Dr. Harrison H. (Jack) Schmitt,** Apollo 17 Astronaut: 12th and last man and only geologist to step on the Moon. Former U.S. Senator (NM). Aerospace and Earth Science Consultant and Director Orbital ATK, Associate Fellow of Engineering Physics at the University of Wisconsin–Madison.

NASA astronaut geologist 1965-1975; He flew as Lunar Module Pilot on Apollo 17 and as the only scientist and the last man to step on the Moon. Dr. Schmitt continues to play an active role in Apollo scientific investigations, particularly through synthesizing field observations with sample analyses and recent remote sensing data. He also has worked in energy policy formulation, including establishing and heading NASA's Energy Program Office 1974-1975, consulting with the Fusion Technology Institute at the University of Wisconsin-Madison, and advocating lunar energy and other resource utilization. Dr. Schmitt's 2006 book, *Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space,* proposes the advancement of private sector acquisition of lunar helium-3 as a fuel for commercial fusion power reactors. Dr. Schmitt received a Bachelor of Science degree from the California Institute of Technology in 1957; studied as a Fulbright Fellow at the University of Oslo in Norway during 1957-1958; and received a doctorate in geology from Harvard University in 1964. He was elected and served as the U.S. Senator representing New Mexico 1977-1983. Dr. Schmitt became Chair of the NASA Advisory Council in 2005, serving until 2008. He is an associate fellow of engineering physics at the University of Wisconsin–Madison. He produced Chapter 2 - Lunar Helium-3 Energy Resources in the AAPG-EMD Memoir 101 produced by the Astrogeology Committee and Energy Minerals Div., AAPG. See page 73. Dr. Schmitt lives in the intermountain West with his wife, Teresa Fitzgibbon, and a number of four-legged canine family members.

**Dr. James (Jim) Reilly,** NASA astronaut geologist; Mach 25 Management, Colorado Springs, Colorado, USA

Exploration Geologist Enserch Exploration, Inc., 1980-1995; NASA astronaut on shuttle missions STS-89 in 1998, STS-104 in 2001 and STS-117 in 2007. He has logged over 853 hours in space, including 5 spacewalks totaling 31 hours and 10 minutes. Reilly retired from NASA in May, 2008. He is currently principal with Mach 25 Management engaging corporate, public sector, and student audiences around the world. Dr. Reilly also serves as the curriculum developer and instructor for a mid-career course for military personnel in Space Operations via the National Security Space Institute operated by the Air Force in Colorado Springs, CO. He is actively involved with senior and graduate level engineering projects with students at the University of Colorado, Colorado. Springs, the US Air Force Academy, and Stevens Institute of Technology. His research interests include systems engineering for future Mars exploration missions and surface operations on Mars. Dr. Reilly earned his Bachelor of Science degree in geosciences from University of Texas-Dallas, 1977, Master of Science degree in geosciences from University of Texas-Dallas, 1987, and Doctorate in geosciences from University of Texas-Dallas, 1995. He produced Chapter 7 - Avoiding Extraterrestrial Claim Jumping ....in Memoir 101, see p. 73.

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**Dr. Kent Sundell,** Geology Department Chair and Instructor Casper College, Casper, Wyoming, USA

Dr. Kent A. Sundell is Department Chair and Instructor Casper College, Casper, Wyoming. Kent starred in BBC's paleontology documentary *Walking with the Beasts*. Dr. Sundell also the owner and sole proprietor of Douglas Fossils and has collected more than 5,000 skulls and skeletons of fossil mammals and reptiles from private lands in Converse County, Wyoming. Dr. Sundell has taught geology and paleontology at Casper College in Casper, Wyoming for 20 years. Common specimens, such as oreodonts, camels, horses, rabbits, rhinos, turtles, dogs and sabertooth cats are sold to private collectors, museums and teaching institutions around the world. Rare undescribed specimens, such as snakes, amphisbaenids, tiny rodents, insectivores, and marsupials are provided to museums and research institutions around the world for study, description, publication, curation, and final display.

***Tyrannosaurus rex* at Casper College**

**Oreodont skull**

**Don Clarke:** Consulting Petroleum Geologist, Lakewood, CA, USA

Consulting Petroleum geologist who lives and works in southern California. He retired from his civil service work with the City of Long Beach (Unit Operator for the Giant Wilmington oil field) and the California State Lands Commission in 2004. His clients include Occidental Petroleum, California Resources Corporation, the Cities of Beverly Hills, Newport Beach and Hermosa Beach, Mid Con Energy, Emerald Energy, Geomechanics Technologies, Glamour Magazine and others. Don served on two committees for the National Research Council and was on the Board of Directors for the National PTTC and the Dibblee Foundation. Don has been active in the AAPG and has served the association in many ways and received many awards. Don has had a lifelong interest in astronomy and paleontology.

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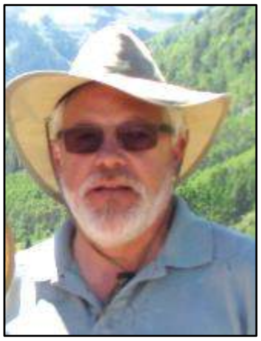
**Doug Cook:** Chair AAPG Astrogeology Committee. Colorado Springs, Colorado, USA



Doug Cook is recently retired (April, 2016) as Chief Explorationist of Saudi Aramco's Southern Area Exploration Division in Saudi Arabia. While there, in addition to oil and gas exploration, Doug explored and published on five impact structures and led desert star gazing trips for the Dhahran Geoscience Society. Before joining Aramco, Doug explored deep water Gulf of Mexico and Nigeria for Conoco and BHP. A career highlight aside from prospecting was participating in ten years of deep water submersible oil seep studies in the Gulf of Mexico. These seeps have associated chemosynthetic communities of life. As extremophiles, these organisms relate to Doug's passion for astrogeology/exobiology. Doug received his BS in Oceanography from the University of Michigan and MS in Carbonate Sedimentology from the University of Florida prior to joining Conoco in 1984. He is a member of American Association of Petroleum Geologists (AAPG), Chair AAPG Astrogeology Committee, Society of Exploration Geophysicists (SEG), and Member-at-Large with Colorado Springs Astronomical Society. Doug currently teaches Astronomy at Pikes Peak Community College.

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**Karl Osvald:** Senior Geologist at Bureau of Land Management, Casper, Wyoming, USA

Karl's expertise in local Wyoming geology and astrogeology has been indispensable in assisting to organize our astrogeology field work at Linch, Sussex, and Douglas, WY.

Mr. Osvald is a senior geologist with the Bureau of Land Management (BLM) Wyoming State Office's Reservoir Management Group. He is currently the Wyoming technical lead for Geologic Carbon Sequestration; EOR; UIC; Oil Shale/Tar Sands, Shale Gas/Shale Oil, Geothermal & Helium; University of Wyoming--BLM Assistance Agreement Representative; Wyoming BLM-DOE Research Partnership Coordinator; and has served as a member by appointment to the Governor of the State of Wyoming's GIS Oversight Committee. Parallel with his Geoscience career, Mr. Osvald served thirty-two years in the USAF Reserve, retiring as Major, Reserve. Mr. Osvald's Geoscience promotion and outreach efforts include serving as a current member, and past Chairman, of the Tate Geological Museum Advisory Board, Tate Geological Museum, Casper College, Casper, Wyoming. As a founding member of the Planetary Society, he is a lifelong advocate of planetary exploration, human potential growth and expansion of our species into the Cosmos. His broader topical interests in embrace Planetary Geology, Paleontology, Archaeology, and History; particularly what is coming to be known as "Big History".
Mr. Osvald is a graduate of the University of Georgia, and he has taught, under the auspices of the BLM's Intergovernmental Personnel Act(IPA) program, at the university level as a professor, Zoology & Environmental Science, Engineering Technical Communications & Research Seminar, South Carolina State University, Orangeburg, S.C. He is also a member of the Advisory Group to the Uranium (Nuclear and Rare Earth) Committee of the Energy Minerals Division (AAPG).

## AAPG 2017 Eclipse Seminar Packing List

Expect daytime temperatures in the field to be 85 to 95 F in the sun. A quick summer thunderstorm can drop temps into the low 60s quickly. We will have two days in field and you will have the opportunity to participate some world-class geology and paleontology sites. Sample and fossil collecting will be allowed unless directed otherwise. We will have food and water in the vans.

**FIELD GEAR**

- Day pack.
- Guidebook (provided on check-in Aug 18).
- Notebook and pen/pencil.
- Good hiking boots (over the ankle) required (sharp rocks and rattlesnakes possible).
- Long pants required (rough brush and rattlesnakes possible).
- Hat and sunscreen required.
- Insect repellant.
- Medications if necessary.
- Energy snack optional.
- T-shirt with a long-sleeve light colored shirt layered over is practical.
- Walking stick(s) optional. Most terrain moderate. Some terrain is challenging (optional participation).
- Light rain poncho optional.
- Hand lens optional.
- Rock hammer and chisel optional.
- Eye protection if using rock hammer.
- Fossil brush optional.
- Specimen bags for collecting. Sandwich bags.
- Sharpie marker.
- Camera, batteries, SD cards,( charger).
- One quart ziplock plastic bags to hold rocks and fossils
- Aluminum foil to wrap fossils
- Blue painter’s tape to hold the foil on
- Band aids
- Market carry bags for fossil finds
- Facial tissues
- Wet wipes

## AAPG Field Safety & Health Considerations

| | |
|---|---|
| **Field Environmental Conditions** | Elevations at Wyoming field sites range from about 1,340 to 2,350 meters (4,400 - 7,700 ft). Typical daytime temperatures are 28 to 30 °C (82 to 86 °F), but you should be prepared for temperatures from 8 to 35°C (46 °F to 95 °F). Brief, intense rainstorms are possible. Strong winds and blowing dust are possible. Vegetation is a typical high-desert/steppe assemblage (sage, pine, cactus, and greasewood), so expect to encounter thorny brush and cacti.<br>Venomous snakes, spiders, and insects exist in the field areas but are not commonly encountered by school groups. Ticks are present locally in Wyoming and may carry disease (Rocky Mountain Fever and Lyme Disease). |
| **Description of Field Terrain** | The field seminar will make hikes of short to intermediate duration (20-90 minutes) with mostly moderate elevation gain (10-20 meters) in occasionally rough, rocky terrain, with thorny brush.. The most strenuous day involves a voluntary hike that covers 2 km (1.3 miles) with an elevation gain of 70 meters (225 ft) during the course of about 90 minutes. |

## Identification of Potential Safety Hazards

| | |
|---|---|
| **Slips, Trips, and Falls** | There are trip and fall hazards on ledges and loose rocks on hillsides and trails. |
| **Rock Hammers** | *Caution using rock hammers and chisels. Eye protection is required.* |
| **Personal health / hazardous conditions** | • Poor physical conditioning may lead to overexertion and severe fatigue which can exacerbate pre-existing medical conditions and contribute to accidents. As detailed in the attached form, participants with certain serious medical conditions must check with their physician or health services department prior to attending this school. *See attached* ***Emergency Contact and Medical Certification*** *form.*<br>• Allergic reaction to insect bite or plant puncture wound<br>• Heat-related illness / dehydration<br>• Sunburn |

# AAPG Field Safety Briefing

**Personal health hazardous conditions**

- **Candidates should determine their ability to handle short periods (20 -90 minutes) of high exertion at relatively high altitudes, which are required to access some of the field localities. Vertical change in elevation will be 70 m (225 feet) or less at base elevations of 1,500 m (5,000 feet).**
- Persons under medical care or taking daily medications are advised to consult with their physician or health services department prior to committing to participate in the activity. It would also be helpful to alert the Field Activity Leader of any special medications you may be taking before any emergency situation arises.
- Persons with known dangerous allergies to insect bites, foods, etc. should make such allergies known to the Field Activity Leader so that the appropriate care can be taken of you in the event of an emergency.
- Sun block, insect repellant, and proper clothing are needed to reduce the chance of sunburn, insect bites, and overexposure.

**Behavior based risks**

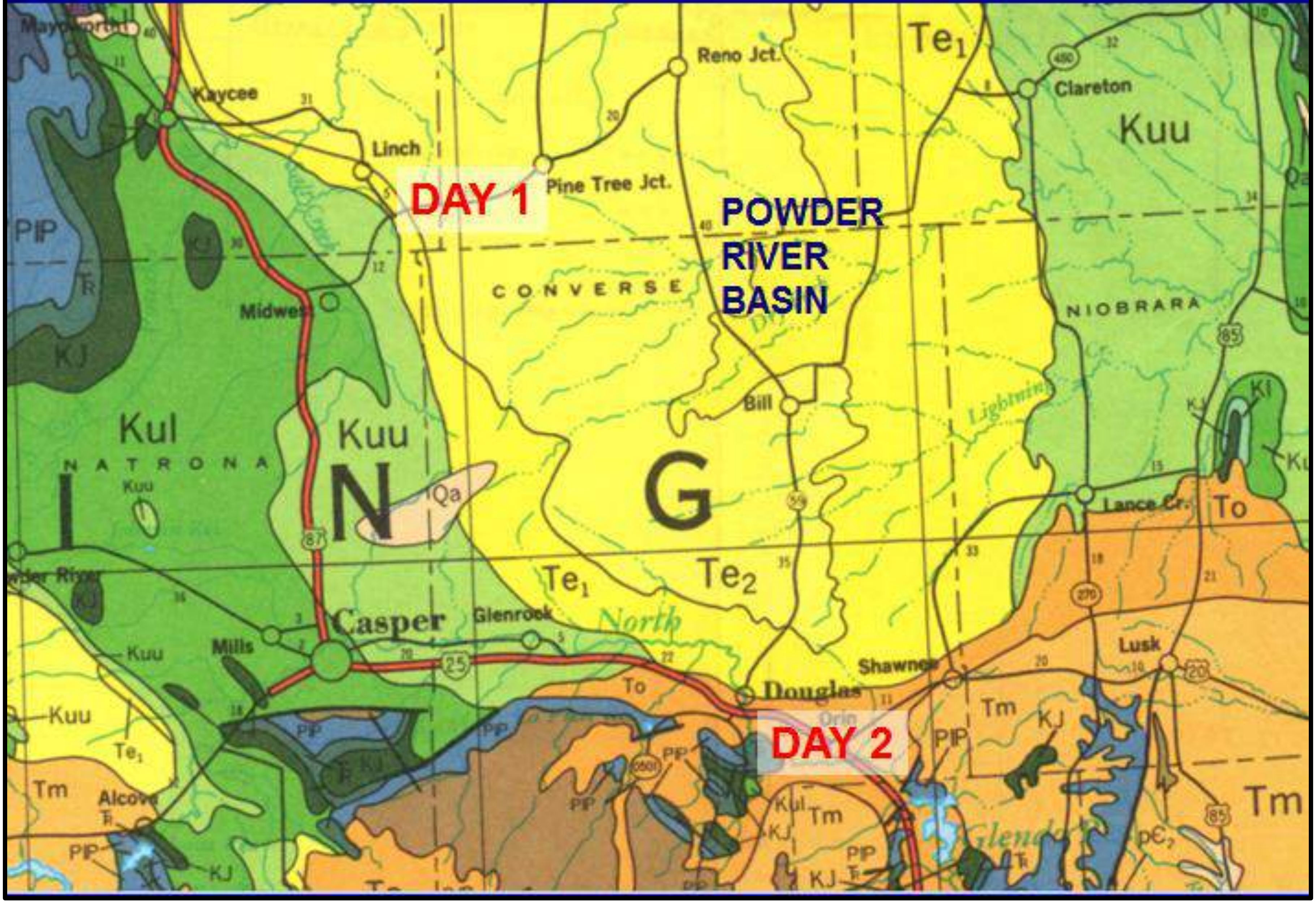
- All participants are required to follow the risk assessment and standard operating procedures identified in this pre-trip letter, any trip or site specific orientations, and\or any safety instructions given by the activity staff.
- All participants are required to self identify any discomfort or pain associated with all field activities. Do not continue to participate is you are experiencing pain or have exceeded your personal tolerance for fatigue / risk acceptance. Notify a member of the staff and arrangements will be made to modify the activity or provide an alternate level of participation.
- Any deviation from these required behaviors are grounds for removal from the field activity.

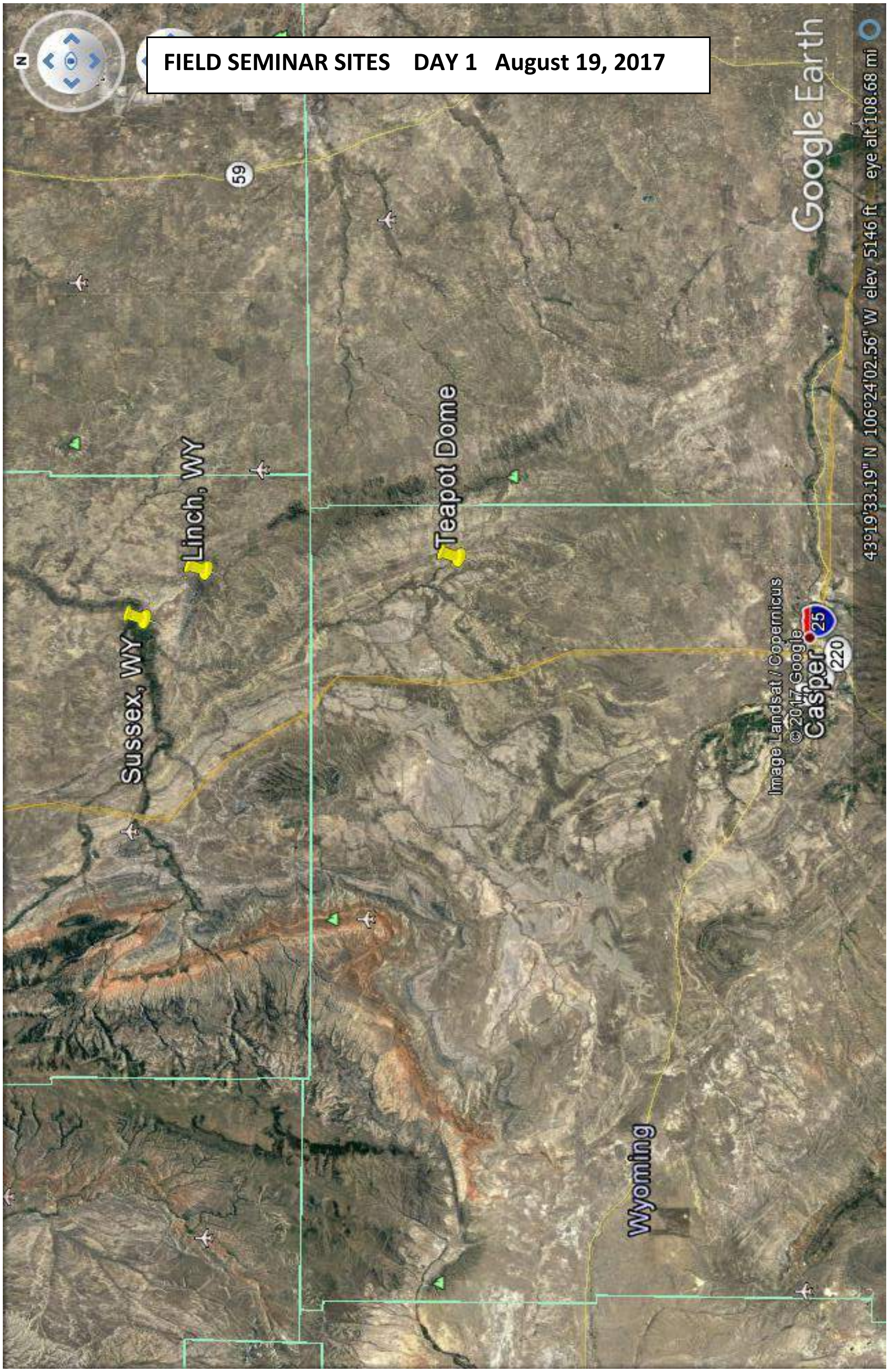
**Motor vehicle hazards**

- **Personnel driving vehicles are required to take defensive driving training. This, or a similar driver education program, is strongly recommended for all persons wishing to drive field vehicles.** Van drivers will be provided by Casper College.

- **All Participants should pay careful attention to periodic briefings by the Field Activity Staff on potentially hazardous conditions associated with use of the vehicles.**

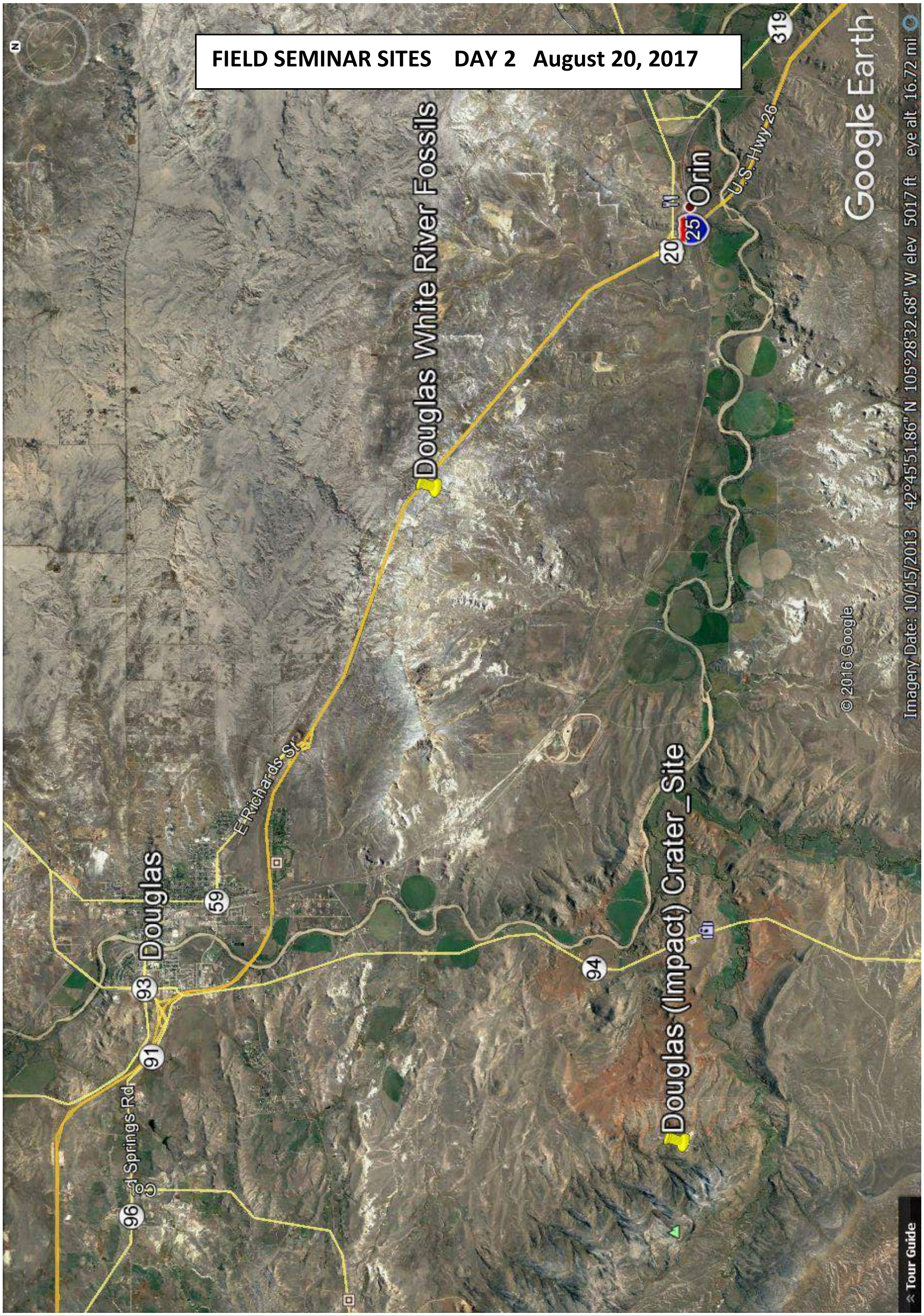
# GEOLOGIC MAP Casper, WY



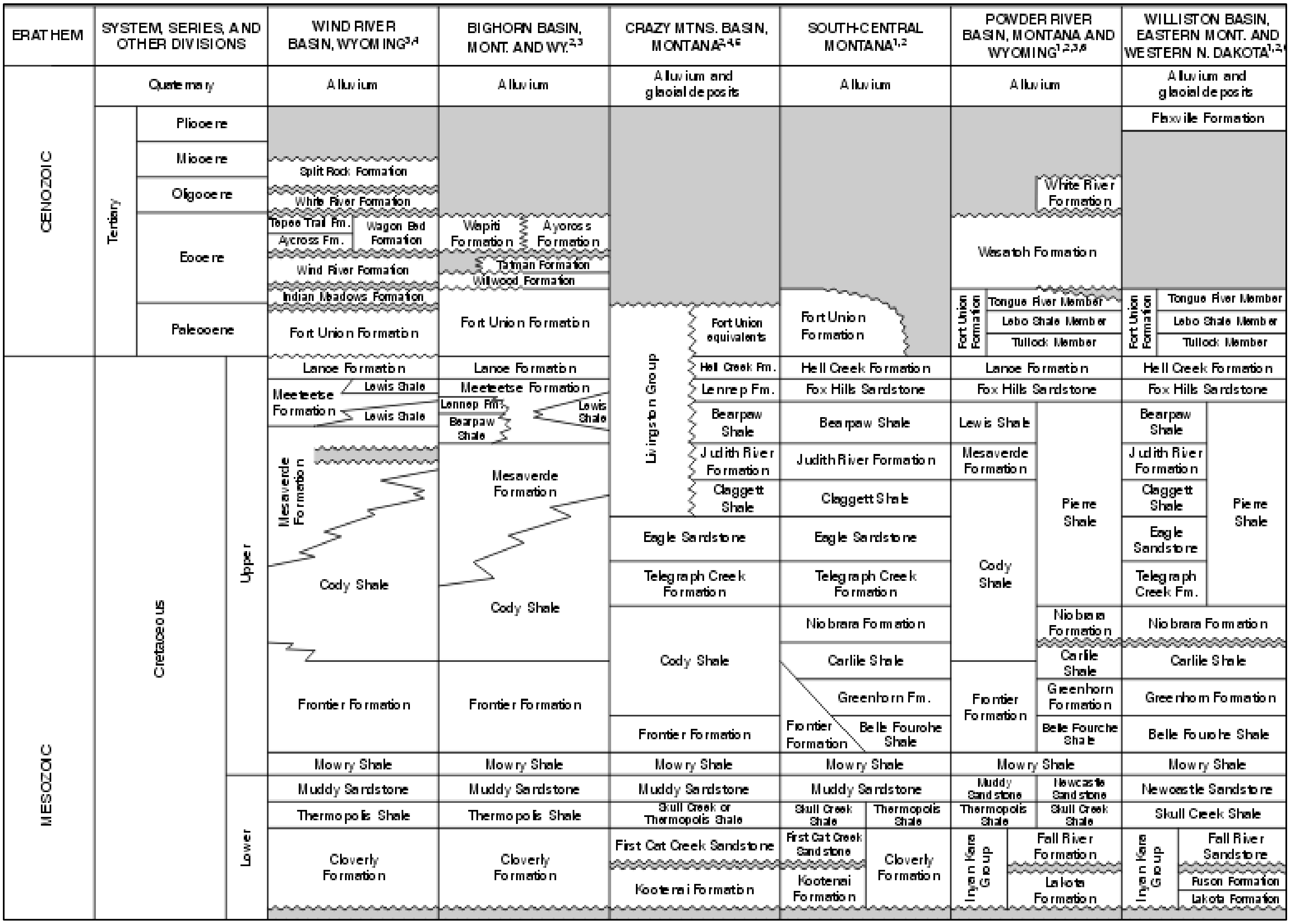


**FIELD SEMINAR SITES DAY 1 August 19, 2017**

## FIELD SEMINAR SITES DAY 2 August 20, 2017

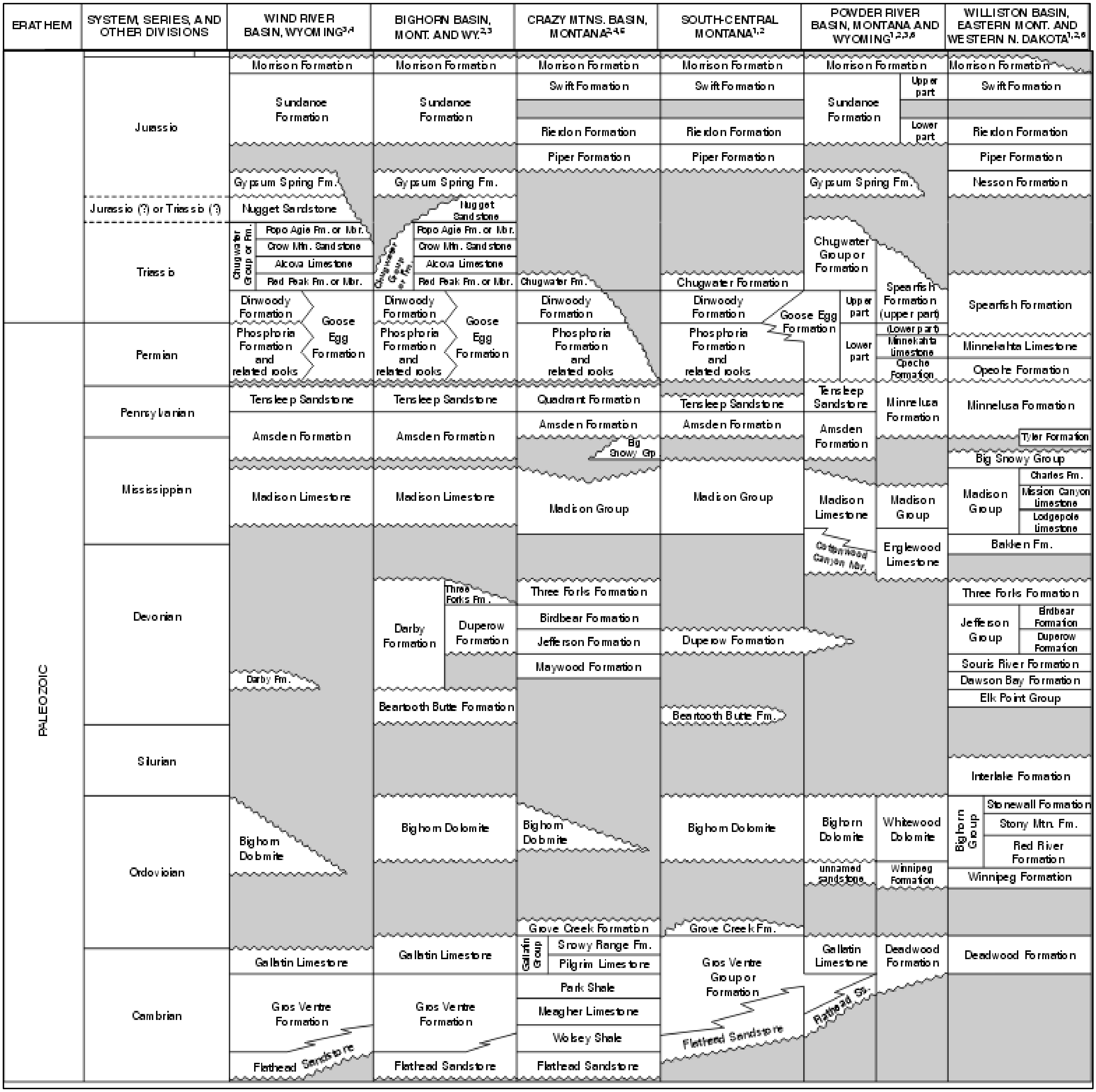


# WYOMING STRATIGRAPHIC NOMENCLATURE CHART

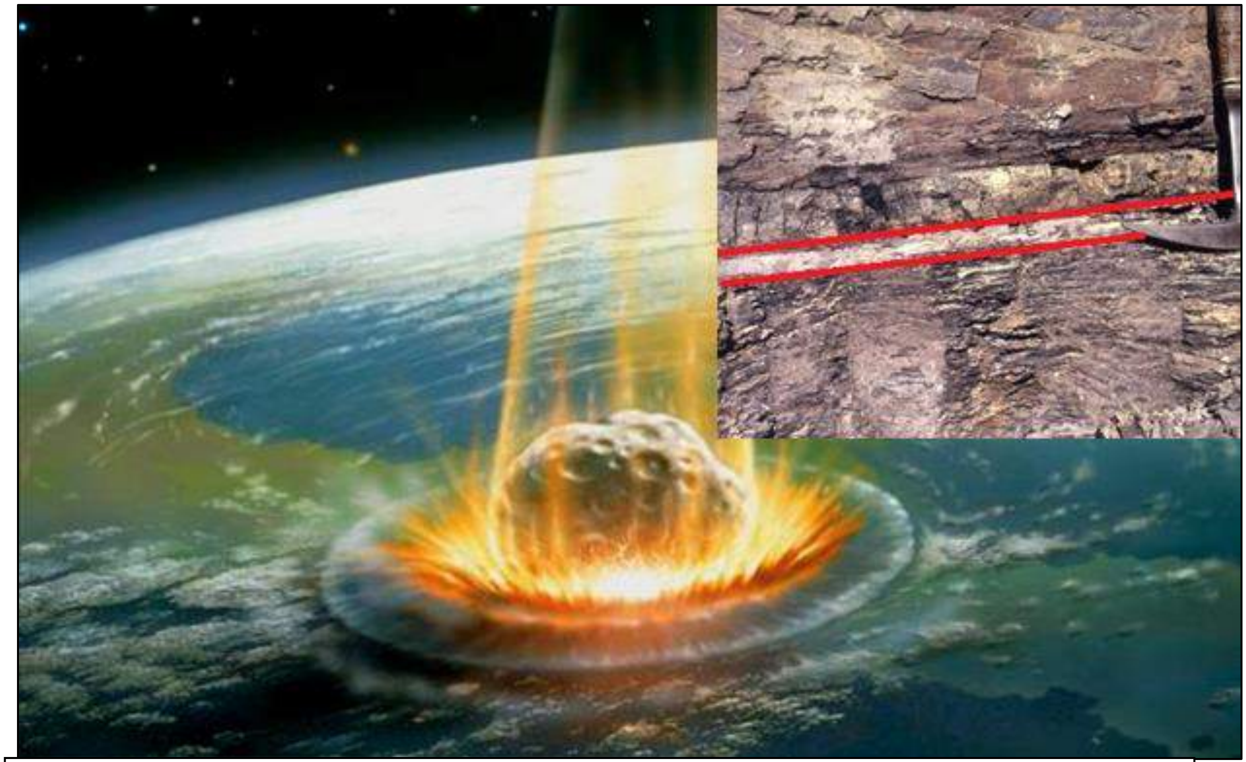


| ERATHEM | SYSTEM, SERIES, AND OTHER DIVISIONS | | | WIND RIVER BASIN, WYOMING$^{3,4}$ | BIGHORN BASIN, MONT. AND WY.$^{2,3}$ | CRAZY MTNS. BASIN, MONTANA$^{2,4,5}$ | SOUTH-CENTRAL MONTANA$^{1,2}$ | POWDER RIVER BASIN, MONTANA AND WYOMING$^{1,2,3,6}$ | WESTERN N. DAKOTA / WILLISTON BASIN, EASTERN MONT. AND WESTERN N. DAKOTA |
|---|---|---|---|---|---|---|---|---|---|
| CENOZOIC | Quaternary | | | Alluvium | Alluvium | Alluvium and glacial deposits | Alluvium | Alluvium | Alluvium and glacial deposits |
| | Tertiary | Pliocene | | | | | | | Flaxville Formation |
| | | Miocene | | Split Rock Formation | | | | | |
| | | Oligocene | | White River Formation | | | | White River Formation | |
| | | Eocene | | Tepee Trail Fm.<br>Aycross Fm.<br>Wagon Bed Formation<br>Wind River Formation<br>Indian Meadows Formation | Wapiti Formation<br>Aycross Formation<br>Tatman Formation<br>Willwood Formation | | | Wasatch Formation | |
| | | Paleocene | | Fort Union Formation | Fort Union Formation | Livingston Group<br>Fort Union equivalents | Fort Union Formation | Fort Union Formation<br>Tongue River Member<br>Lebo Shale Member<br>Tullock Member | Fort Union Formation<br>Tongue River Member<br>Lebo Shale Member<br>Tullock Member |
| MESOZOIC | Cretaceous | Upper | | Lance Formation | Lance Formation | Hell Creek Fm. | Hell Creek Formation | Lance Formation | Hell Creek Formation |
| | | | | Meeteetse Formation<br>Lewis Shale<br>Lewis Shale | Meeteetse Formation<br>Lennep Fm.<br>Lewis Shale | Lennep Fm. | Fox Hills Sandstone | Fox Hills Sandstone | Fox Hills Sandstone |
| | | | | | Bearpaw Shale | Bearpaw Shale | Bearpaw Shale | Lewis Shale<br>Pierre Shale | Bearpaw Shale<br>Pierre Shale |
| | | | | Mesaverde Formation | Mesaverde Formation | Judith River Formation | Judith River Formation | Mesaverde Formation | Judith River Formation |
| | | | | | | Claggett Shale | Claggett Shale | Cody Shale | Claggett Shale |
| | | | | Cody Shale | Cody Shale | Eagle Sandstone | Eagle Sandstone | | Eagle Sandstone |
| | | | | | | Telegraph Creek Formation | Telegraph Creek Formation | | Telegraph Creek Fm. |
| | | | | | | Cody Shale | Niobrara Formation | Niobrara Formation | Niobrara Formation |
| | | | | | | | Carlile Shale | Carlile Shale | Carlile Shale |
| | | | | Frontier Formation | Frontier Formation | | Greenhorn Fm.<br>Frontier Formation | Frontier Formation<br>Greenhorn Formation | Greenhorn Formation |
| | | | | | | Frontier Formation | Belle Fourche Shale | Belle Fourche Shale | Belle Fourche Shale |
| | | | | Mowry Shale | Mowry Shale | Mowry Shale | Mowry Shale | Mowry Shale | Mowry Shale |
| | | Lower | | Muddy Sandstone | Muddy Sandstone | Muddy Sandstone | Muddy Sandstone | Muddy Sandstone<br>Newcastle Sandstone | Newcastle Sandstone |
| | | | | Thermopolis Shale | Thermopolis Shale | Skull Creek or Thermopolis Shale | Skull Creek Shale<br>Thermopolis Shale | Thermopolis Shale<br>Skull Creek Shale | Skull Creek Shale |
| | | | | Cloverly Formation | Cloverly Formation | First Cat Creek Sandstone | First Cat Creek Sandstone<br>Cloverly Formation | Inyan Kara Group<br>Fall River Formation | Inyan Kara Group<br>Fall River Sandstone |
| | | | | | | Kootenai Formation | Kootenai Formation | Lakota Formation | Fuson Formation<br>Lakota Formation |

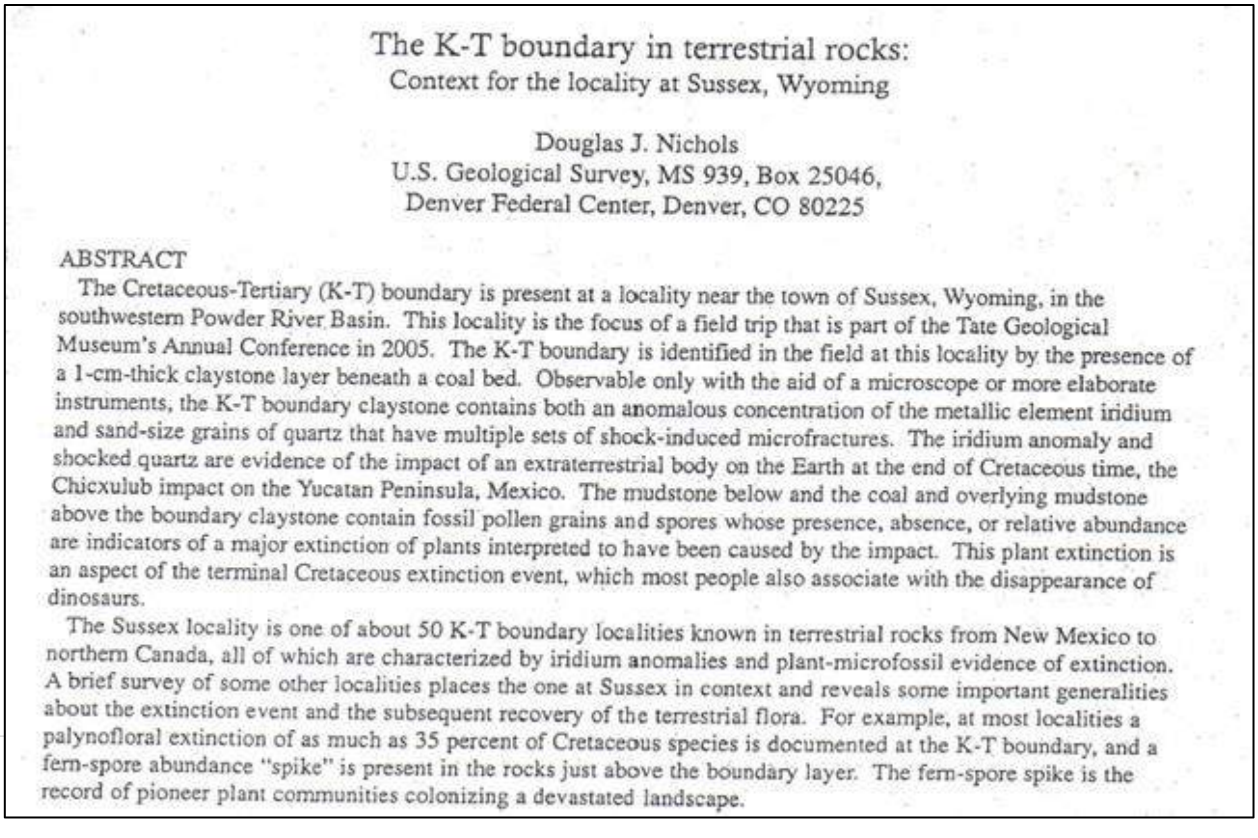
# WYOMING STRATIGRAPHIC NOMENCLATURE CHART



# LINCH and SUSSEX, WY FIELD DAY 1 AUGUST 19, 2017



**11th Annual Tate Symposium of Paleontology and Geolog**y, 2005
Paper included on Flash Drive



## The K-T boundary in terrestrial rocks:

### Context for the locality at Sussex, Wyoming

Douglas J. Nichols
U.S. Geological Survey, MS 939, Box 25046,
Denver Federal Center, Denver, CO 80225

ABSTRACT

The Cretaceous-Tertiary (K-T) boundary is present at a locality near the town of Sussex, Wyoming, in the southwestern Powder River Basin. This locality is the focus of a field trip that is part of the Tate Geological Museum's Annual Conference in 2005. The K-T boundary is identified in the field at this locality by the presence of a 1-cm-thick claystone layer beneath a coal bed. Observable only with the aid of a microscope or more elaborate instruments, the K-T boundary claystone contains both an anomalous concentration of the metallic element iridium and sand-size grains of quartz that have multiple sets of shock-induced microfractures. The iridium anomaly and shocked quartz are evidence of the impact of an extraterrestrial body on the Earth at the end of Cretaceous time, the Chicxulub impact on the Yucatan Peninsula, Mexico. The mudstone below and the coal and overlying mudstone above the boundary claystone contain fossil pollen grains and spores whose presence, absence, or relative abundance are indicators of a major extinction of plants interpreted to have been caused by the impact. This plant extinction is an aspect of the terminal Cretaceous extinction event, which most people also associate with the disappearance of dinosaurs.

The Sussex locality is one of about 50 K-T boundary localities known in terrestrial rocks from New Mexico to northern Canada, all of which are characterized by iridium anomalies and plant-microfossil evidence of extinction. A brief survey of some other localities places the one at Sussex in context and reveals some important generalities about the extinction event and the subsequent recovery of the terrestrial flora. For example, at most localities a palynofloral extinction of as much as 35 percent of Cretaceous species is documented at the K-T boundary, and a fern-spore abundance "spike" is present in the rocks just above the boundary layer. The fern-spore spike is the record of pioneer plant communities colonizing a devastated landscape.

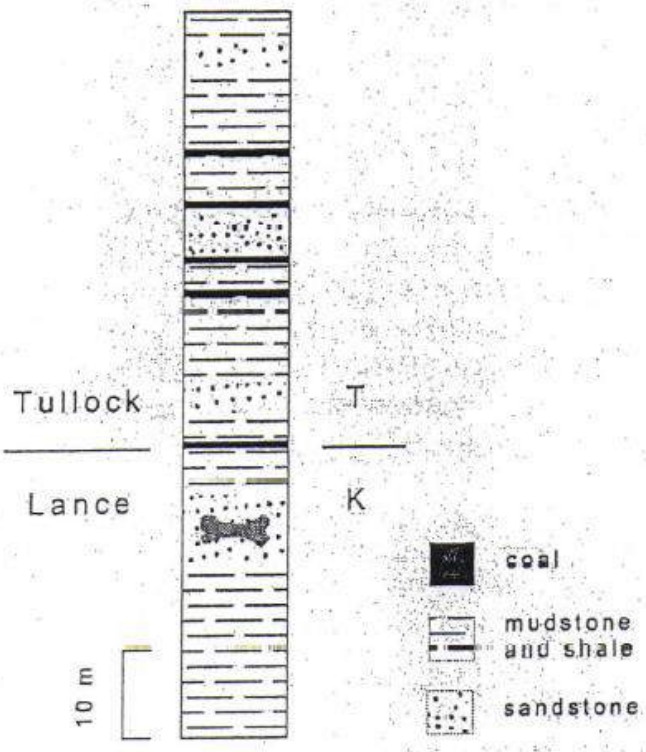


Figure 5. Diagram showing part of the stratigraphic section at the Sussex locality. The section includes the uppermost part of the Lance Formation (Cretaceous, K) and lowermost part of the Tullock Member of the Fort Union Formation (Tertiary, T). The K-T boundary is at the base of a coal bed. A fragment of dinosaur bone was found in Lance sandstone at about the position indicated by the cartoon (m, meters).

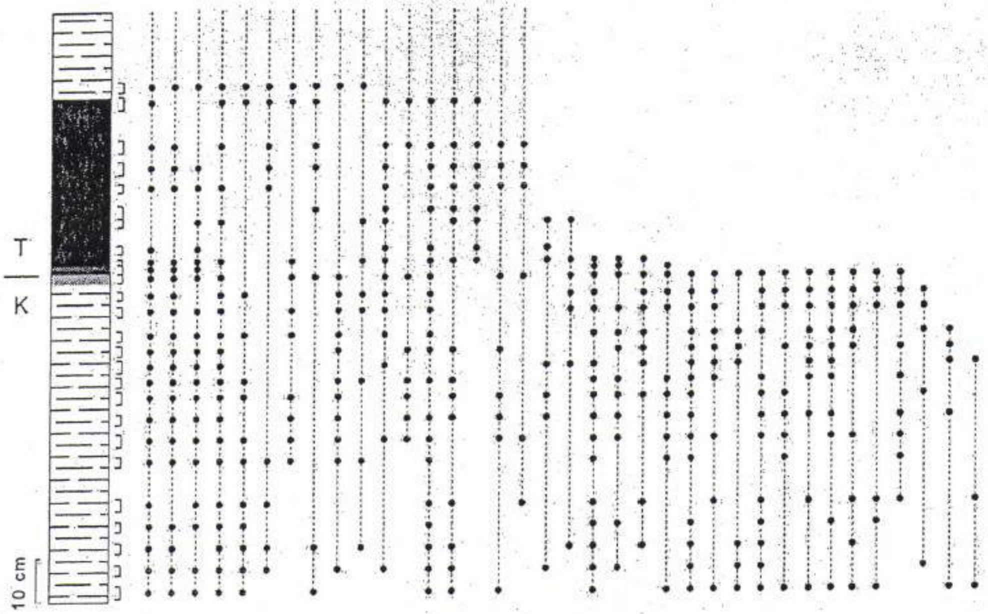
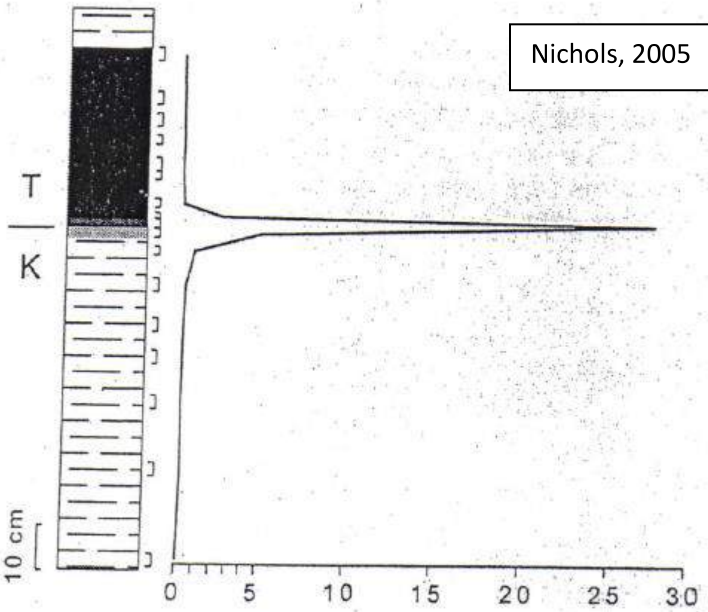


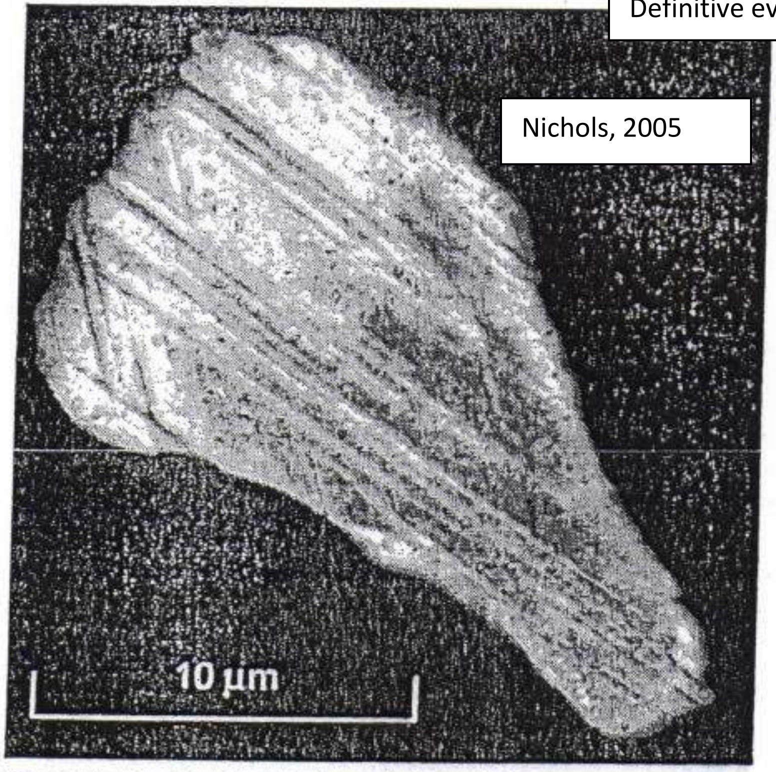
Figure 10. Stratigraphic range chart of pollen and spores at the Sussex locality. Each vertical row of dots represents a particular kind of pollen grain or spore. Each dot indicates that pollen or spores of that kind were found in a particular sample. Sample positions are indicated by brackets to right of section diagram. K-T boundary layer and overlying carbonaceous layer indicated by shaded bands; other lithologic symbols as in figure 5.



Nichols, 2005

Figure 12. Diagram showing the iridium anomaly at the Sussex locality. Units are in parts per billion. Note the very low background concentration of iridium above and below the K-T boundary claystone. Lithologic symbols as in figures 4 and 9 (cm, centimeters).

Iridium anomaly and shocked quartz planar deformation features (PDFs): Definitive evidence of impact origin.



Nichols, 2005

Figure 13. A grain of shocked quartz from the Sussex locality. The grain shows two intersecting sets of parallel microfractures. Length of grain 0.22 millimeters. Photo by G. A. Izett, USGS.

# FIELD TRIP ROAD LOG DAY 1   AUGUST 19, 2017

## STOP 1     Salt Creek Ranch Cretaceous Dinosaur Fossils

## STOP 2-3  Cretaceous/Paleogene extinction boundary, caused by large asteroid impact at Chicxulub, Mexico Yucatan, 65.5 million years ago.

| **Start** La Quinta Inn, Casper, Wyoming | **DIST.** | **CUM.** |
|---|---|---|
| Headed south from parking lot turn right onto frontage road to Poplar Street. | **0.1 mi** | **0.1 mi** |

Cross Poplar and enter northbound Interstate 25. Proceed north on I-25 and past northern portions of Casper and Bar Nunn, Wyoming.

To the south beyond the city of Casper lies **Casper Mountain**, an east-west trending 25 mile long mountain uplift created during the Laramide Orogeny (100- 45Ma). Its top at 8,300' lies about 3,000' higher than Casper. It is a rather asymmetrical east-west trending breached (to Precambrian) anticline with a 25-mile-long fault defining its northern margin with 8,000' of stratigraphic offset. The trace of the fault is easily observed by the break in the slope, vegetation changes, and rock type changes along its entire length. Defining the steep pine covered steep north face of Casper Mountain. At Casper Mountain Road switch backing up the north face 2.8 BA Precambrian granites, granitic gneisses, and schists are thrust northward over the 80 Ma marine Cody Shale that underlies most of Casper.

As we proceed north, away from Casper Mountain, we are in the Powder River Basin. The Powder River Basin is one of the most energy rich geologic basins within the United States containing classic oil & gas resources, uranium resources, coal resources, coal-bed-methane, unconventional shale oil & gas, more than half of the U.S. uranium resources, and recently developed wind power. All major uplifts surrounding the Powder River Basin were formed during the Laramide Orogeny, including the Bighorn Mountains to the west, Casper Mountain, the Laramie Range to the South, and the Black Hills uplift to the East.

The Laramide Orogeny from 100Ma to 45Ma was a compressional event creating the Wyoming Foreland Province along the east edge of the Cordilleran. It produced large amplitude folding and reverse faulting involving sedimentary and Precambrian basement, forming N-S, NW-SE, and E-W structures throughout Wyoming and adjacent states. It was caused by shallow subduction of the Kula Plate along the western edge of the North American plate prior to creation of the proto-San Andreas system. Since the end of the Laramide in middle Eocene, most tectonism has been extensional with normal faulting related to relation after compression and under plating of the Rockies with remnants of the Kula Plate, leading to epeirogenic uplift of all mountains and basins in Wyoming throughout the Neogene of more than 4,000 feet. Hence, Casper and everywhere we will be traveling is over 5,000' in elevation with our highest mountains of 12,000- 13,000' in northwestern Wyoming.

Wardwell Road underpass (exit 191). Town of Bar Nunn to the west. **2.8 mi 2.9 mi**

Teapot Sandstone Member of the upper Cretaceous Mesaverde Formation form the grey cliffs and ridgeline to the west. The Teapot Sandstone is composed of non-marine eolian dunes with a thin coal commonly present below the sandstone. The entire Mesaverde Formation to the east is covered by a Quaternary dune field obscuring its relations to the east. The Teapot Sandstone is overlain by marine shales within the Fox Hills Sandstone Formation.

**4.1 mi 7.0 mi**

Ormsby Road underpass (exit 197). At 3 o'clock, 2 miles east of the interstate, is Midway Oil Field, discovered in 1931 on a structural dome. Midway has produced more than 500,000 BO from the Frontier Formation. **1.7 mi 8.6 mi**

Cross McPhereson Draw. Leaving Quaternary sand dune covered area to south. The Hill at 1 o'clock is capped by the non-marine Lance Formation of latest Cretaceous age (68-65 Ma). From here we slowly descend down section, encountering older rocks, for about 20 miles. The community of Antelope Hills to the East is built on the Lance and Fox Hills formations of late Cretaceous age. **4.7 mi 13.3 mi**

Crest of Twenty Mile Hill. Last view of Casper Mountain to the south. **3.9 mi 17.2 mi**

**Exit Interstate 25 at Exit 210. Turn right (north) onto U.S. Highway 259. 5.2 mi 22.4 mi**

The Late Cretaceous Fox Hills Sandstone is well exposed along the skyline to the right (east) of the Highway 259. It is composed of marine offshore bars sandstones and is usually underlain and overlain by organic rich dark shales (Lewis Shale equivalents). The Fox Hills is a classic unconventional horizontal well play in the Powder River Basin. Fracking both the sandstone and adjacent shale source rocks to release primary (non-migrated) oil and gas. 1 and 2 mile long horizontal lateral wells have been drilled in the Fox Hills. We will drive along strike of this out crop for about 4 miles. **1.1 mi 23.5 mi**

To the left (west) the ponderosa pine covered outcrops are the Teapot Sandstone Member of the Mesaverde Formation. The sandstone is commonly light grey on outcrop and has a thin coal beneath the sandstone in outcrops to the west. **1.5 mi 25.0mi**

Type Locality of Teapot Sandstone Member of Mesaverde Formation is on the point of the hill to the west. **1.7 mi 26.7 mi**

Teapot Ranch with the iconic Teapot Rock hoodoo standing behind it. A tornado in 1962 removed the spout from the teapot form. **0.3 mi 27.0 mi**

Bridge over Teapot Creek. For the next 4 miles we will drive down section through the Mesaverde Formation, gradually changing from eolian dunes to fluvial swampy coals, organic shales, mudstones and thin sandstone channels to a thick marine shoreline facies named the Parkman Sandstone Member of the Mesaverde Formation. **0.8 mi 27.8 mi**

Yellowish sandstone outcrops to the east (across Teapot Creek) are the Parkman Sandstone Member of the Mesaverde Formation. This thick transitional beach to off shore bar sandstone commonly containing *Inoceramus* clams is also a non-conventional horizontally drilled target in the deeper Powder River Basin to the east. **1.6 mi 29.4 mi**

The dark, tree-covered ridge on the skyline to the northeast is the "Pine Ridge" composed primarily of Paleocene Fort Union Formation . To the southeast the pine covered hills are the Teapot Sandstone and the skyline cliff is the overlying Fox Hills Sandstone. **0.4 mi 29.8 mi**

Parkman Sandstone Member of Mesaverde Formation on both sides of the road near the contact with the underlying Cody Shale. **1.7 mi 31.5 mi**

Entrance to Teapot Dome, formerly U. S. Naval Petroleum Reserve # 3. Made nationally famous by a scandal where Albert Fall (Head of Dept. of Interior for U.S.) was leasing and accepting bribes from Harry Sinclair in 1922, The field was developed and most primary production was removed in 1976-2015 after the first Arab oil embargo. It was sold to a private company, Natrona County Holdings, in 2015. Teapot Dome is a south east plunging appendage to the much larger Salt Creek Oilfield. The Shannon and the Second Wall Creek (Frontier Fm.) Sandstones are the dominant petroleum reservoirs, but eight other zones, including the Cody Shale, Niobrara Shale, Third Wall Creek, Muddy Sandstone, Dakota Sandstone, Lakota Sandstone, Morrison Formation, and Tensleep Formation have produced hydrocarbons. **2.2 mi 33.7 mi**


43°18'57.35" N 106°15'16.64" W elev 5065 ft

Enter southern end of Salt Creek Oilfield. Bighorn Mountains are barely visible to northwest.

**1.0 mi 34.7 mi**

The large square bluff directly to the east is called Castle Rock. It is formed by a resistant top of the Shannon Sandstone. The other bluffs are all formed by the Shannon Sandstone Member of the Cody Shale being more resistant to weathering than the overlying and underlying Cody Shale.

**1.6 mi 36.3 mi**

Cross Salt Creek. Cody Shale exposed in cliff faces along creek. **3.4 mi 39.7 mi**

**Turn Right (east) on to Highway 387** at the steel derrick and wooden pumping beam. **0.4 mi 40.1 mi**

Remnants of the early days in the 20th century when thousands of such structures dotted the landscape over Salt Creek Oilfield. Originally discovered in 1889, Salt Creek is the second largest oil field by production in the Rocky Mountains and is the largest producer of Cretaceous-sourced sweet crude oil. A $CO_2$ injection and secondary recovery project was initiated about 10 years ago on the prolific Wall Creek Sandstones and has greatly boosted production again. The enormous 20 mile long by 10 mile wide north-south trending domal structure lies along the western margin of the Powder River Basin. More than nine zones produce oil at Salt Creek with total cumulative production now exceeding 1 billion barrels of oil. Town of Midwest, Wyoming lies west of this intersection. (Possible rest room stop at Big D Gas Station, Midwest, WY).

Shannon Sandstone outcrop to the north along roadside. **0.6 mi 40.7 mi**

Edgerton, Wyoming. **0.5 mi 41.2 mi**

Contact between Cody Shale below and base of Mesaverde Formation. **1.2 mi 42.4 mi**

Cross bridge. Excellent view of the Teapot Sandstone Member of the uppermost Mesaverde Formation with a thin coal visible along creek to the east. **1.4 mi 43.8 mi**

Oil field and out crops of the Fox Hills Sandstone to the right (south). **1.0 mi 44.8 mi**

Contact between the Fox Hills sandstone and the overlying Lance Formation. **1.0 mi 45.8 mi**

Johnson County/ Natrona County boundary while driving up section through the non-marine fluvial, dinosaur bearing Lance Formation. **2.2 mi 48.0 mi**


43°30'39.36" N 106°09'47.24" W elev 5444 ft

**STOP #1 Cretaceous Dinosaur Fossils at Salt Creek Ranch** Turn right and proceed through green gate onto private land of the Salt Creek Ranch to search for dinosaur bone fragments within the Lance Formation. The most common dinosaur in the Lance Formation is *Triceratops* with large horn and frill fragments commonly exposed at the surface without digging. The Tate Museum at Casper College has been collecting the Lance Formation both near this locality and along the west, south, and eastern margins of the Powder River Basin for the past 15 years, discovering the best *Tyrannosaurus rex* ever from Wyoming, about six *Triceratops* specimens, one *Torosaurus* specimen, several hadrosaurs, and pieces of *Pachycephalosaurus*, *Ankylosaurus*, *Dromeosaurus* and many turtles, croc, fish materials associated with dinosaurs in the stream channels that form much of the Lance Formation.

***Triceratops***

Thick massive sandstone forms cliffs and waterfall (when raining) to the right of Highway. This area was reportedly called dinosaur draw when they built the highway due to the occurrence of numerous dinosaur bones encountered. **1.1 mi 49.1 mi**

Top of hill on Pine Ridge. Approximate contact between the latest Cretaceous Lance Formation and the overlying Paleocene Fort Union Formation, but not well exposed. Metal gate to the right leads to private property that has a dinosaur quarry the Tate Museum has been digging on the past three years. It is mainly a broken up and tumbled *Triceratops* at the base of a sandstone channel. Possibly an ALTERNATIVE STOP if muddy roads are an issue or extra time is available. **0.6 mi 49.7 mi**

Cross Meadow Creek driving up section through Fort Union Formation. **1.8 mi 51.5 mi**

Turn left on to Wyoming Highway 192 following Pine Ridge northward in Fort Union Fm. **2.2 mi 53.7 mi**

43°32'36.32" N 106°07'41.31" W elev 5315 ft

Turn left into town of Linch, Wyoming and entrance to Meadow Creek Oil Field. **5.5 mi 59.2 mi**

**ALTERNATIVE STOP** if wet roads proceed down Highway 192 to road cut containing various Paleocene plant fossils – approximately .5 miles then return to Linch.

43°36'16.82" N 106°11'36.66" W elev 4978 ft

Passing large tank battery at Meadow Creek Oil Field. Keep Right. **0.3 mi 59.5 mi**

Cattle Guard. Crossing on to private land. Fort Union Formation.

Old Homestead to left (west). Dinosaur bones reportedly used to adorn the front porch. **0.9 mi 60.4 mi**

Turn right off oil field road onto dirt 2-track towards Sussex Dinosaur K/T extinction boundary site.

**3.7 mi 64.1 mi**

Travel along 2-track to base of symmetrical hill. **0.3 mi 64.4 mi**

## STOP #2 Sussex K/T Boundary site (reference paper Nichols, 2005).

## 43° 37' 53.11" N 106° 19'59.21" W

Return to turnoff for Teapot Dome Oil Field (log mile 33.7) and turn east (left). (Possible rest room stop at Big D Gas Station, Midwest, WY). **30.6 mi 95.0 mi**

43°18'57.35" N 106°15'16.64" W elev 5065 ft

Black Gate at entrance to Teapot Dome (Natrona County Holdings- Operator). **0.5 mi 95.5 mi**

Teapot Creek Bridge. Driving on Cody Shale. **0.3 mi 95.8 mi**

Hilltop. Excellent view of Teapot Dome Oil Field. Rim Rocks of Shannon Sandstone several miles to the north towards Salt Creek Oil Field. Resistant ridge of sandstones within the Mesaverde Formation ring the east, south, and west sides of the large domal structure. Core of dome breached to Cody Shale where most oil facilities are located. Pine Ridge visible to the east along the skyline is formed by resistant sandstones in the Fort Union Formation. **1.5 mi 97.3 mi**

Geology Office at Headquarters for Teapot Dome operations. **1.5 mi 98.8 mi**

Gate. Leaving Teapot Dome onto private land. Cross contact between Cody Shale and Parkman Sandstone at the bottom of the Mesaverde Formation. **2.7 mi 101.5 mi**

Beautiful exposures of Mesaverde Formation badlands to left (north). **3.8 mi 105.3 mi**

Turn left at Cattle guard on road to Ranch House. Pine tree-covered ridge is the Teapot Sandstone at the top of the Mesaverde Formation. **0.4 mi 105.7 mi**

Excellent view of 40 degree east dipping Fox Hills Sandstone, **2.4 mi 108.1 mi**

Salt Creek. Approximate contact between Fox Hills Sandstone and Lance Formation. **1.3 mi 109.4 mi**

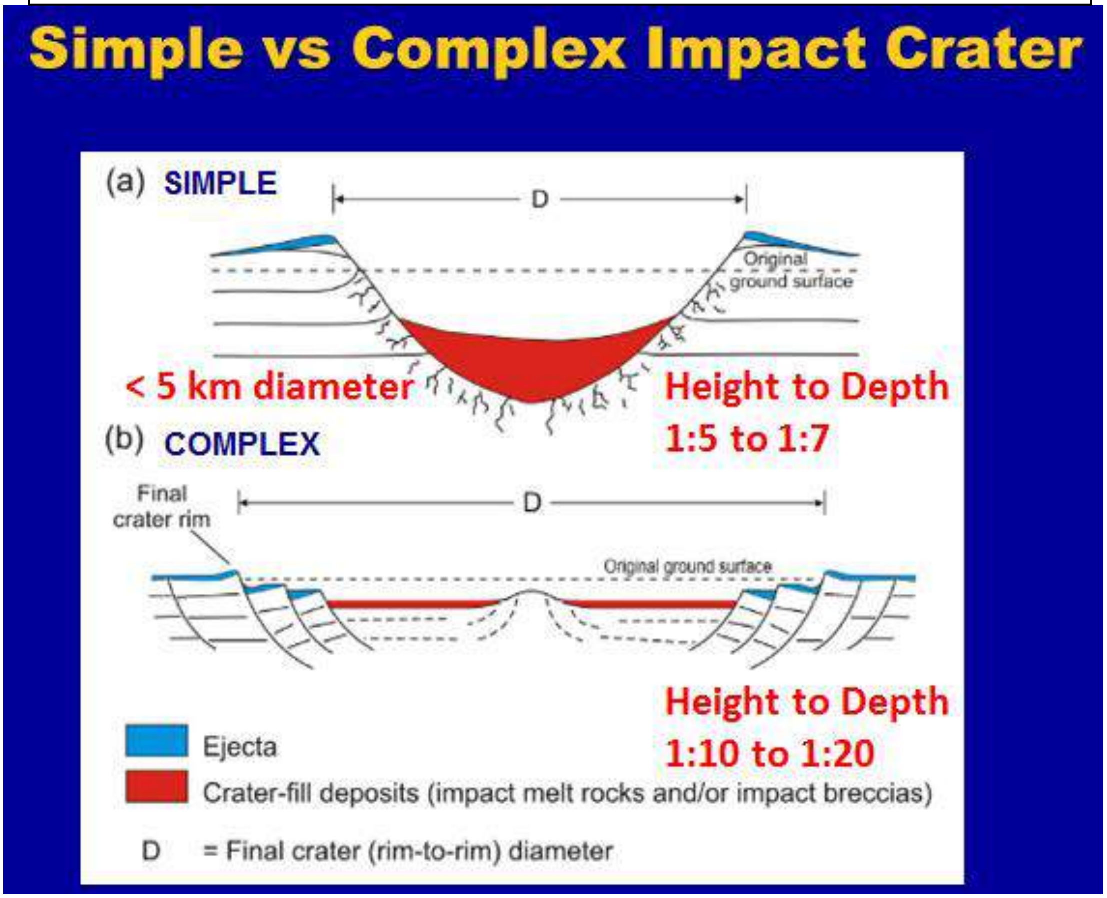
## STOP #3 Lily Pond site of K/T boundary (reference paper Wolfe, 1991) 6.9 mi 116.3 mi

## 43° 15’ 08” N 106° 03’ 57” W

This site contains evidence by Jack Wolfe of multiple asteroid impacts at the Cretaceous/Paleocene boundary. Second possible dinosaur bone collecting site is possible if time is available.

**Return to Casper and La Quinta Inn planned by 4:30 PM. 54.4 mi 170.7 mi**

**END FIELD DAY**

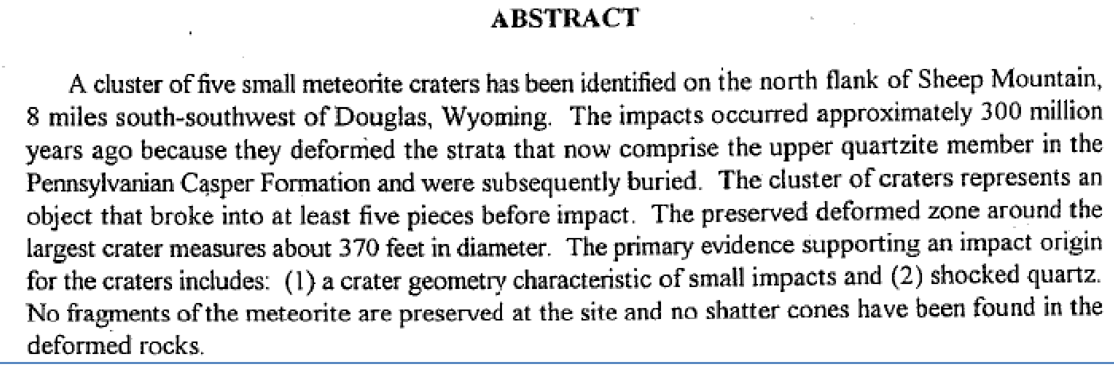

Simple vs Complex Impact Crater

< 5 km diameter

Height to Depth
1:5 to 1:7

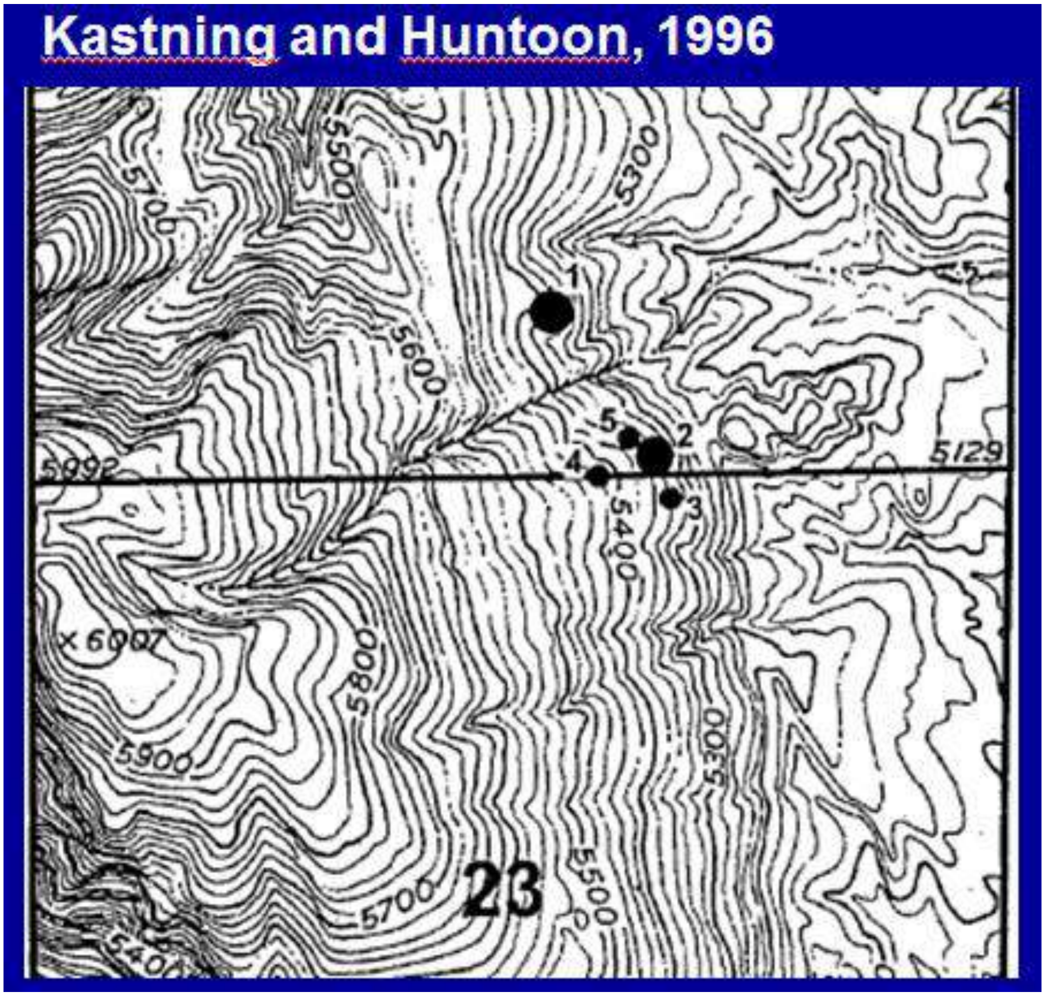
Height to Depth
1:10 to 1:20

**Kastning, H., and P. W. Huntoon, 1996, Cluster of five small Pennsylvanian meteorite impact craters on Sheep Mountain near Douglas, Wyoming: in, T. M. Ciardi and P. E. Johnson, eds., NASA's Wyoming Space Grant Fellowship Program 1995-6 Space Science Research: Wyoming Space Grant Consortium, University of Wyoming (Laramie, WY), p. 57-64 (on flash drive).**


## ABSTRACT

A cluster of five small meteorite craters has been identified on the north flank of Sheep Mountain, 8 miles south-southwest of Douglas, Wyoming. The impacts occurred approximately 300 million years ago because they deformed the strata that now comprise the upper quartzite member in the Pennsylvanian Casper Formation and were subsequently buried. The cluster of craters represents an object that broke into at least five pieces before impact. The preserved deformed zone around the largest crater measures about 370 feet in diameter. The primary evidence supporting an impact origin for the craters includes: (1) a crater geometry characteristic of small impacts and (2) shocked quartz. No fragments of the meteorite are preserved at the site and no shatter cones have been found in the deformed rocks.

# STOP 1 Douglas, WY IMPACT CRATERS



Kastning and Huntoon, 1996 Figure 1 Table 1 (feet)

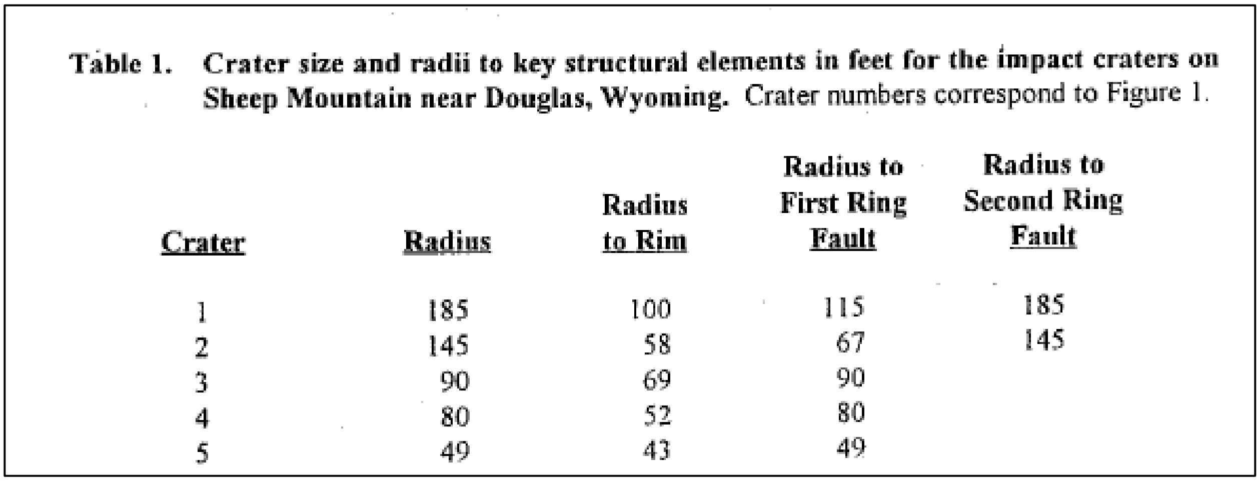


**Table 1. Crater size and radii to key structural elements in feet for the impact craters on Sheep Mountain near Douglas, Wyoming.** Crater numbers correspond to Figure 1.

| **Crater** | **Radius** | **Radius to Rim** | **Radius to First Ring Fault** | **Radius to Second Ring Fault** |
|---|---|---|---|---|
| 1 | 185 | 100 | 115 | 185 |
| 2 | 145 | 58 | 67 | 145 |
| 3 | 90 | 69 | 90 | |
| 4 | 80 | 52 | 80 | |
| 5 | 49 | 43 | 49 | |

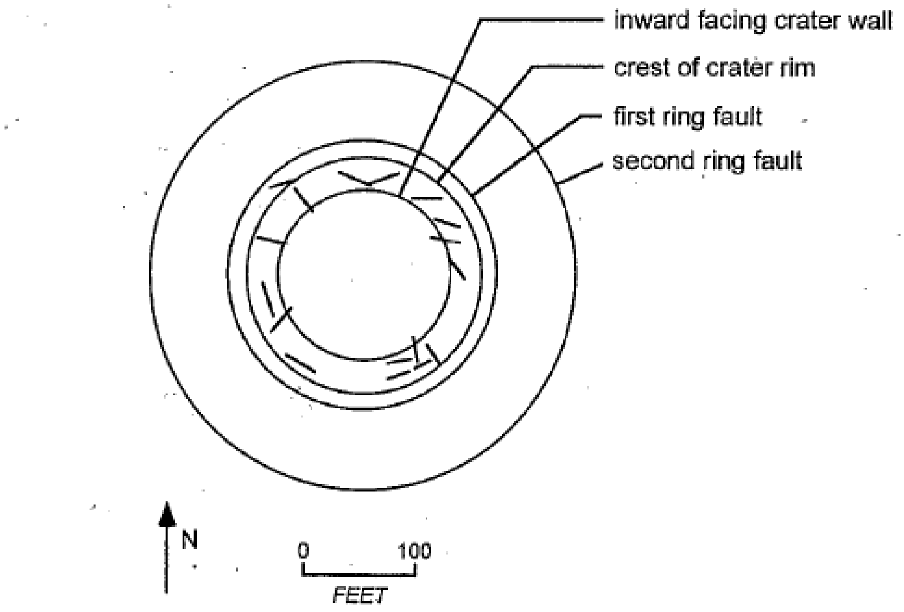


Figure 2. Idealized sketch map of Crater 1 showing the location of various ring features, and the locations and orientations of the maximum principal stresses (short line segments) deduced from conjugate shears.

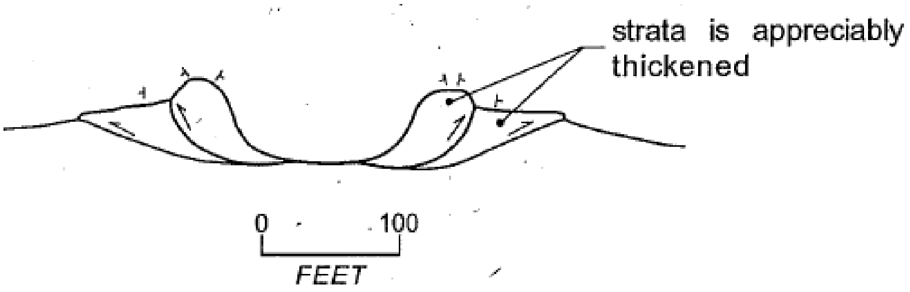
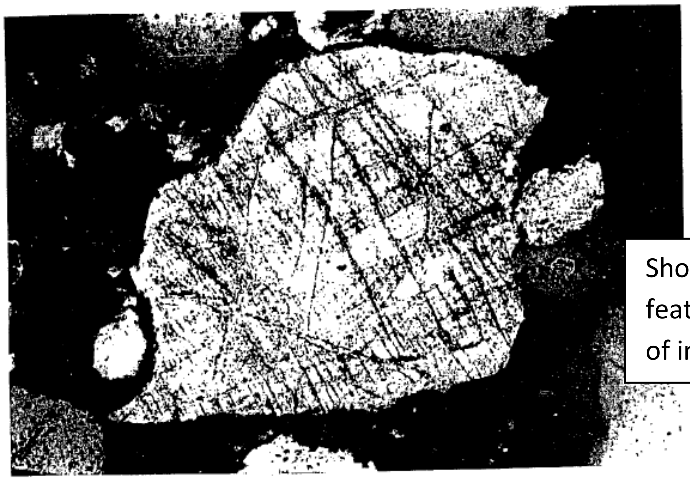


Figure 3. Simplified structural profile through Crater 1. Dip symbols show the attitude of the strata at the surface in the displaced rings. The vertical scale is exaggerated.

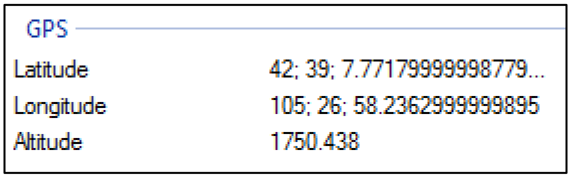


Shocked quartz planar deformation features (PDFs): Definitive evidence of impact origin.

Figure 4. Thin section from floor of crater 1 showing shocked quartz which has definitive parallel lines called planar deformation features.

## Douglas, Wyoming  CRATER 1  DRONE PICTURE

60 meters long axis.   Oriented NW to SE, presumed direction of impact.

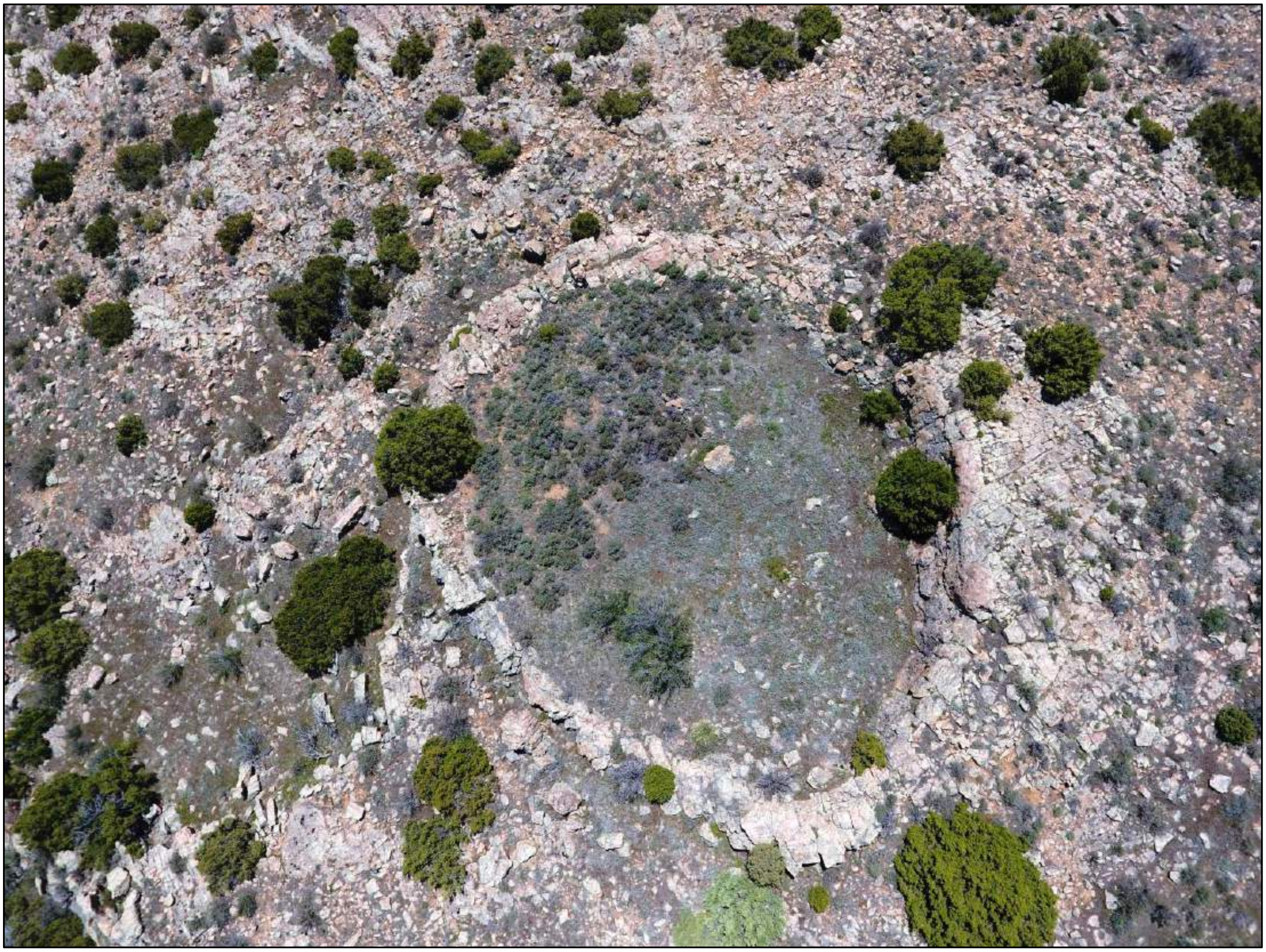


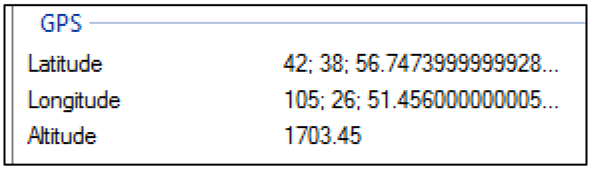
GPS

| | |
|---|---|
| Latitude | 42; 39; 7.77179999998779... |
| Longitude | 105; 26; 58.2362999999895 |
| Altitude | 1750.438 |

## Douglas, Wyoming  CRATER 2  DRONE PICTURE

31 meters long axis.   Oriented NW to SE, presumed direction of impact.





GPS

| | |
|---|---|
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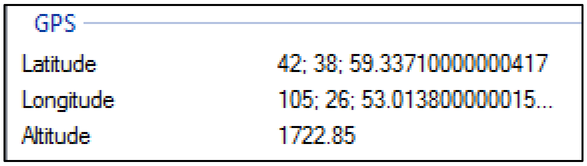
| Altitude | 1703.45 |

## Douglas, Wyoming CRATER 3 DRONE PICTURE

35 meters long axis. Oriented NW to SE, presumed direction of impact.



GPS

| | |
|---|---|
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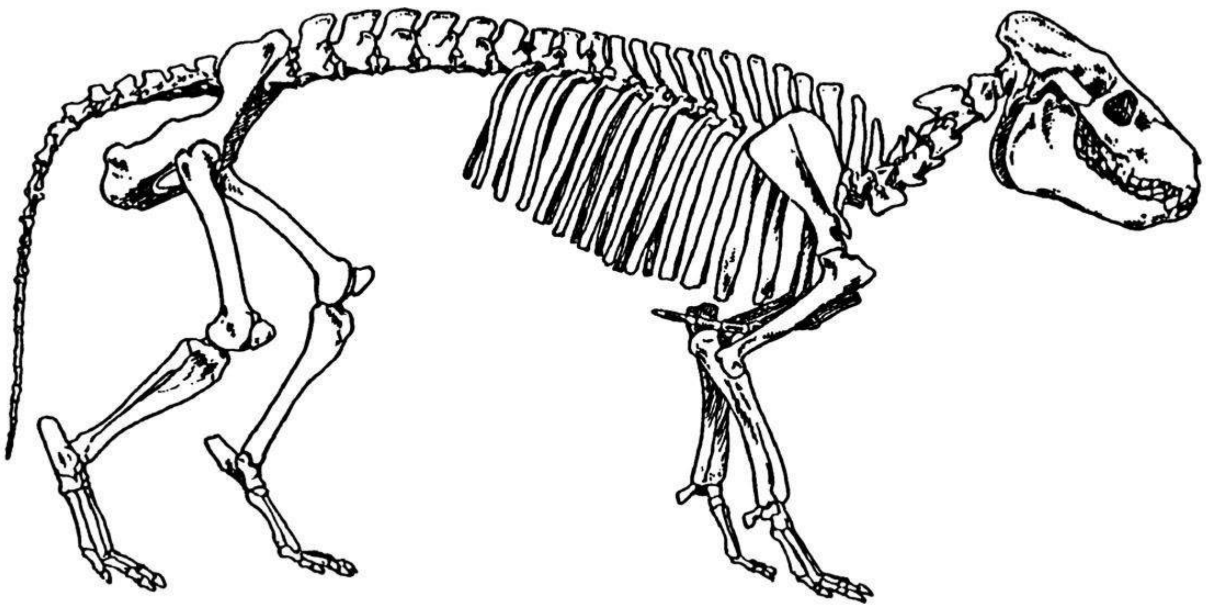
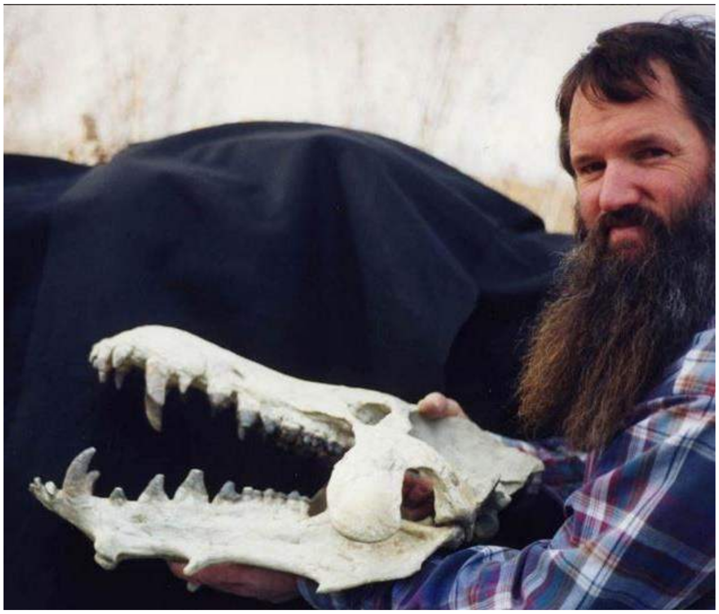
| Altitude | 1722.85 |

## Oreodont- Common fossil in White River Fm. (Late Eocene-Oligocene)



The Oreodont *Merycoidodon culbertsoni*
(after Scott, 1936)

**STOP 2** Scenic badlands featured in numerous paleontology films (Walking with Prehistoric Beasts-BBC, Razor Jaws-Nat Geo, Killer Pigs-Nat Geo, Dawn of the Cats-Paleoworld, Valley of the Uglies-Paleoworld) and be allowed to collect Oligocene and late Eocene vertebrate fossils, possibly including saber tooth cats, *Archaeotherium*-killer pig, Hyaenodon-razor jaws, oreodonts, camels, horses, rhinos, deer, rabbits, rodents, insectivores, marsupials, snakes, lizards, and large land tortoises (some > 200 pounds). Dr. Sundell has studied this badlands area for more than 40 years and collected more than 5,000 skulls and skeletons.



**Kent Sundell with *Archaeotherium* skull.**

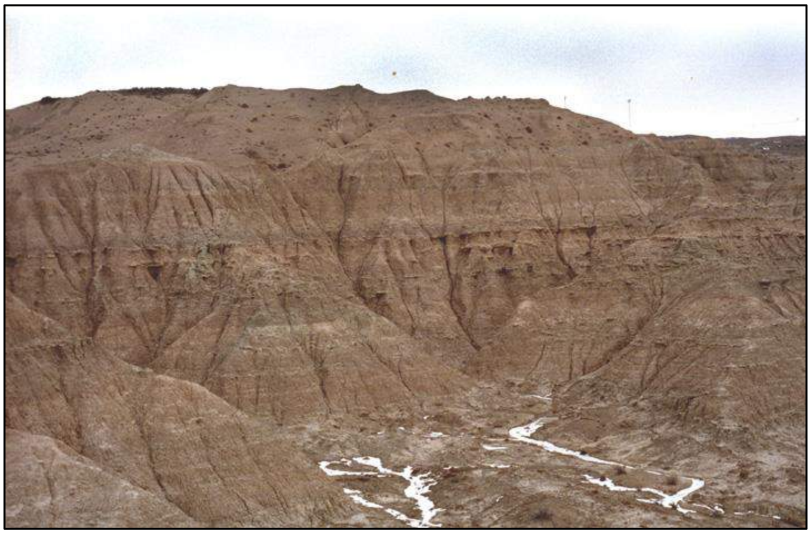
***Archaeotherium*** **skull.**

***Mesohippus*** **skull.**

## *Dinictis felina* (Saber tooth Cat)

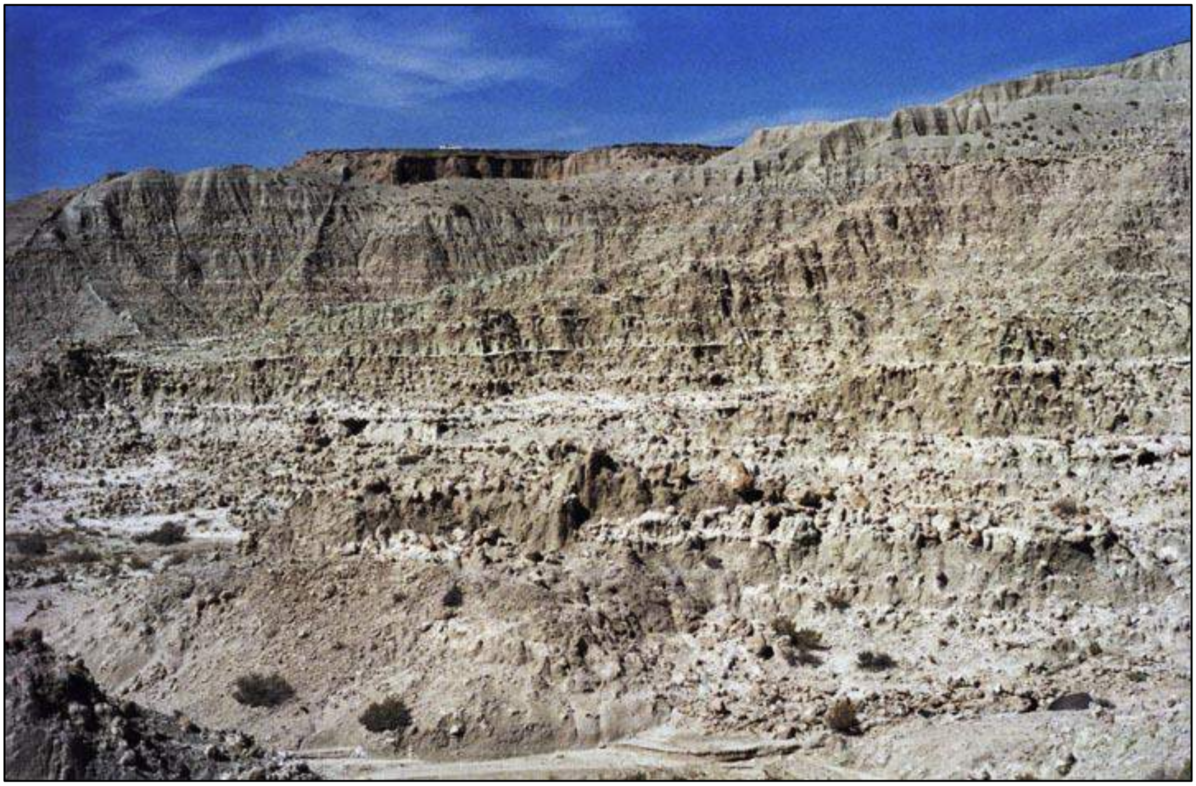
# Paleontology and Geology of the White River Formation

## Geology of the White River Formation:



The White River Formation contains numerous late Eocene and Oligocene vertebrate, invertebrate and plant fossils in the Douglas, Wyoming area. It is composed of terrestrial sedimentary rocks (300 meters thick), including mudstones, siltstones, sandstones, minor conglomerates, and volcanic tuffs.The paleoenvironment was an aggradational meandering river system (ancestoral North Platte River) with the conglomerates and sandstones reflecting the stream channels and mudstones and siltstones deposited during periodic overbank flooding by the river.

It is a classic paleoenvironment for preserving a terrestrial fauna. The occurrence of more than 13 volcanic tuffs within the White River Formation interspersed with numerous excellent fossils and magnetically susceptible rocks provides a unique and scientifically exciting control to the geology of this area that is unparalleled. Only two of the tuffs has been isotopically dated (Tuff #5 age 33.9 Ma, Swisher and Prothero, 1990 and Prothero and Swisher, 1992)(Tuff #5 age 34 Ma, Tuff #7 age 31.2 Ma, J. Scott 2000), but many of the other tuffs can and should be dated. The stratigraphy and invertebrate (snail) paleontology of the area has recently been thoroughly studied by Evanoff (1993 and et.al 1992) with many measured sections and descriptions of the volcanic tuffs. A generalized measured section is presented here from Evanoff's PhD dissertation studies. This co-occurrence of fossils, magnetically stable beds, and datable volcanic tuffs will allow future research in this area to be correlated regionally (Nebraska, South Dakota, western U. S.) and worldwide.



**Vertebrate Paleontology of White River Formation:**

The vertebrate fossils from the Douglas area include spectacular specimens of reptiles (snakes, lizards, tortoises and turtles) and mammals (ancestoral modern lineages: horses, dogs, cats, mustelids, camels, deer, rhinoceros, rodents, rabbits, insectivores, and marsupials and extinct lineages: brontotheres, entelodonts, oreodonts, hyaenodonts, and sabertooth cats). It is the world's best locality for many of the small, delicate, and rare mammals and reptiles of the mid-Tertiary period. The specimens of fossil snakes (Breithaupt, 1997), amphisbaenids (Dickson and Cunningham, 1997), marsupials, insectivores, and rodents are unique and exceptional. This is due to a combination of paleoecology (a burrowing community)(Sundell, K, 1997a and Sundell, C., 1998) and unique preservation conditions (secondary calcite cementation). Well articulated skeletons of many of the larger mammals are also found. Many include unborn fetuses, juveniles, and multiple death assemblages that are unknown scientifically (Sundell, K., 1997a,1997b, 1998). Several local vertebrate and one invertebrate paleontological studies have been done in this area that provide a general biostratigraphic framework (Kron, 1978, Prothero, 1983, and Evanoff, 1993, Evanoff, et. al. 1992). The White River Formation can usually be subdivided into three fossil land mammal ages based on the vertebrate fauna, including the Chadronian, Orellan, and Whitneyan North American Land Mammal Ages (NALMAs) from oldest to youngest, respectively. White River Formation simplified chart). The Chadronian and Orellan faunas have been firmly delineated in the Douglas area, but the Whitneyan fossils are rare in the upper third of the White River Formation at this locality and elsewhere. The change from Chadronian to Orellan faunas occurs very near the one isotopically dated tuff bed. This single date and faunal change has been a key data point for revisions of the Chadronian North American land mammal age from the early Oligocene epoch to the late Eocene epoch (Swisher and Prothero, 1990, Prothero and Swisher, 1992). This important boundary change and the less studied Orellan to Whitneyan boundary can be studied in great detail in the Douglas area. A second key tuff bed has been located slightly above the probable Orellan/ Whitneyan NALMA boundary and tentatively dated at ~31 MA (Scott 2000) with more than 120 meters of Whitneyan fossiliferous rocks occurring above this tuff. The unique interrelations of prolific fossils, radiometric datable tuff beds, and paleomagnetic susceptible sediments from three NALMAs and 5 magnetic Chrons ((9-13) in one geographic location is the primary focus of future research at this locality.

**Paleoecologic significance:** By studying the precise stratigraphic and geographic location of the more than 3,500 skulls and skeletons collected by Douglas Fossils a tremendous data set can be used to help interpret paleoecological changes both vertically (stratigraphic relations to ash beds and evolutionary change through time) and horizontally (geographic lateral changes in the Douglas area and correlations to other White River outcrops in Nebraska, South Dakota, and Colorado). Additionally the forensic analysis of some of the more spectacular specimens (multiple oreodonts, multiple camels, carnivore dens, carnivore killsites, bite marks, coprolites, and leftovers) allows us to better interpret how each of these unique organisms lived their lives and how they died. We have studied in detail and proven many new hypotheses, such as: 1)How Oreodonts lived in burrows much like modern prairie dogs rather than in large herds on the open plains. 2)Hyaenodons (last of the Creodonts) are the dominant predator of Oreodonts and are symbiotically tied to them. 3) Archaeotheriums are dominantly attack predators that bite their prey and battle each other by running alongside and biting the

back of their adversary's skull and swallow them whole or in big gulping chunks similar to crocodiles. The recently discovered Swan Lake plant locality of Orellan age is the first good assemblage of plant material (leaves, trees, roots, grasses, pollen, and phytoliths) to be found in the upper (Oligocene) portion of the White River Formation. The lake deposits are lateral equivalents to the best mammal producing horizons a few miles away (up ancestral-North Platte drainage during Oligocene). Future detail studies of this plant data will proving the rate of climate change across the Eocene/Oligocene boundary in central North America. The phytoliths will eventually be used to show exactly which plants the various herbivores were eating. Dental plaque on ungulate teeth contain phytoliths identified in the plants of Swan Lake. Together the forensic science of "who is eating whom" and which herbivores are eating which plants will result in a true paleoecology of changes in the paleoenvironment from Eocene to the Oligocene within the White River Formation.

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# FIELD TRIP ROAD LOG DAY 2 AUGUST 20, 2017

## STOP 1 Exhumed Paleozoic Meteor Impact Craters near Douglas, WY.

## STOP 2 Mammal Fossils White River Formation (33 Ma) near Douglas, WY.

**Start** La Quinta Inn, Casper, Wyoming **DIST.** **CUM.**

Headed south from parking lot turn right onto frontage road to Poplar Street **0.1 mi** **0.1 mi**

Turn left on Poplar Street, go under overpass and turn left entering south bound **Interstate 25.** **0.1 mi** **0.2 mi**

Hat Six Road exit at easternmost edge of Casper. Note the pine tree-covered grey sandstones within and primarily south of the interchange. This is the Teapot Sandstone Member of the Mesaverde Formation that we saw yesterday. It forms the top of the formation and is overlain by the Fox Hills Sandstone observed for the next several miles as small sandstone outcrops along the interstate and to the north, at 9 0'clock, a broad syncline, plunges northward away from the North Platte River composed of sandstones in the Fox Hills Sandstone Formation of late Cretaceous age. **1.8 mi** **2.0 mi**

As we drive eastward between Casper and Glenrock, Wyoming we traverse the southern margin of the Powder River Basin, driving on upper Cretaceous rocks of the Fox Hills Sandstone, Mesaverde, and Cody Shale Formations. To the south the eastern plunging end of the Casper Mountain structure can be seen with tight folding of the Paleozoic rocks at the easternmost edge of the mountain.

At Glenrock, Wyoming, between the west and east exits, we cross Deer Creek, which heads in the Laramie Mountains about 10 miles south of the interstate. Deer Creek forms a large Canyon that cuts through the dominantly Paleozoic mountain front, exposing Precambrian granites, granitic gneisses, and a variety of high grade metamorphic rocks from 2.8 -3.2 Ba. A large south-dipping thrust fault is exposed at the mouth of Deer Creek Canyon, thrusting Paleozoic carbonates and Precambrian granitic rocks over late Cretaceous shales and sandstones. **24.5 mi** **26.5 mi**

From Glenrock to Douglas, Wyoming we drive eastward along the southern margin of the Powder River Basin and north of the Laramie Range mountain front. The rocks change from Cretaceous sandstones and shales near the Dave Johnson Power Plant east of Glenrock to pinkish mudstones (in road cuts) and resistant pale green coarse sandstone stream channels forming most hard rock outcrops. As we approach Douglas, Wyoming, red, purple, green, tan variegated mudstones may be seen in outcrops north of the interstate often forming low hills. These are Early Eocene Wasatch Formation rocks about 53-55 Ma. The red and purple colors indicate paleosols formed when Wyoming was much warmer and wetter, covered by a heavy canopy forest full of primates, 18 inch tall horses (*Hyracotherium*), and 8 foot tall birds (*Diatryma*) that ate the horses and were top predator at that time.

West Douglas Exit I-25 **21.1 mi 47.6 mi**

Turn right (east) at first stoplight entering Douglas **0.8 mi 48.4 mi**

(Possible rest room stop at Mc Donald's or other Douglas, WY).

Turn right (south) onto Esterbrook Road and go under I-25 overpass **0.3 mi 48.7 mi**

A 10-mile-long, 1,000 foot offset normal fault goes under the town of Douglas, Wyoming separating Early Eocene Wasatch Formation to the north of the Interstate and town of Douglas from Late Eocene and Oligocene White River Formation south of the fault. This fault is part of post-Laramide extensional tectonics, commonly found along Laramide mountain fronts due to relaxation after Laramide compression uplifted the mountains and down warped the basins- in this case forming a graben that began filling with sandstones and mudstones in an aggrading overbank stream system environment (ancestral North Platte River). This change in tectonics coincided with world-climatic change across the Eocene-Oligocene boundary as Antarctica moved to the South Pole and the Earth cooled 15 degrees. The climate change shifted the plants southward causing primates to migrate southward with the heavy canopy forests and eventually forming the New World monkeys in Central and South America. Most of the ungulates (horses, rhinos, camel, deer, etc.) stayed in Wyoming but began adapting to a colder drier climate. The rocks reflect this change by changing colors to tan, pinkish, and pale green colors of a more alkaline and oxidizing environment perfect for preserving bones and teeth, but only rarely are carbonaceous plant fossils preserved.

The "Chalk Butte" cliffs to the right (south) are small remnants of Miocene Ogallala Formation in the center of the graben. They are mainly composed of grey massive ash-rich sandstones containing few fossils. **1.0 mi 49.7 mi**

Esterbrook Road generally follows just south of the North Platte River for the next 6 miles driving across the White River Formation with only a few localized badlands outcrops exposed. In about 4 miles, Jackrabbit Mountain rises up along the north side of the Platte River exposing Mesozoic rocks in a well-exposed north dipping section including the Early Cretaceous Lakota. We will drive along the crest of a breached anticline with Triassic redbeds forming the core surrounded by higher hills of younger Mesozoic rocks, including a very white eolian beach sandstone named the Canyon Springs Sandstone Member of the Sundance Formation.


42º39'54.63" N 105º24'01.75" W elev 4782 ft

Turn right from pavement on to gravel Wagonhound Road headed south. Drive across a tightly folded syncline of Mesozoic rocks and then primarily across redbeds of the Triassic Chugwater Formation. **5.6 mi 55.3 mi**

Cross cattle guard. Rock Quarry and largest impact crater is visible to the south and lies just east (left) of the crushed limestone/sandstone road base quarry. **2.1 mi 5 7.4 mi**

Enter rock quarry private road to the right. The quarry is mining the Casper Formation as road base a mixture of limestone and sandstone. **0.4 mi 57.8 mi**

**Stop # 1 (Day 2) Meteor Impact Craters Site.** Stop before entering quarry at base of north dipping Pennsylvanian age Casper Formation. A porta-potty is available at the parking site. The hike up to the largest impact crater will take about 30 minutes up a moderately steep slope. Several hours will be available to explore the nature of these impacts. Five impacts are reported in the short paper by Kastings and Huntoon, but my recent drone flights indicate probably at least 8 impact craters are observable within about a ¼ mile square area and a possible larger buried impact may occur beneath younger cover rocks where we are parking. The craters are exhumed craters, yet still retain much of the original crater form due to the very hard (quartzite) nature of the upper Casper Formation and soft redbeds of overlying Goose Egg and Chugwater Formations have been eroded off the 25 degree north dipping slope of Sheep Mountain Anticline. The age of impacts is probably late Pennsylvanian, but may be as young as the Permian/Triassic boundary.
**0.3 mi 58.1 mi**

Lunch may be eaten either at the end of this stop before driving to the White River Badlands or at a rest area near the badlands with much better rest room facilities.

Return to Douglas, Wyoming. Turn right at Anderson Dairy Bridge road. **6.6 mi 64.7 mi**

Bridge over North Platte River. **0.6 mi 65.3 mi**

Turn Left (west) on Irvine Road towards Douglas **0.4 mi 65.7 mi**

Under Interstate 25 overpass **0.8 mi 66.5 mi**

Turn Right at stop sign and cross railroad Tracks **0.2 mi 66.7 mi**

Turn Left at stop sign **0.1 mi 66.8 mi**

Turn Right on to Richardson Street in Douglas, Wyoming **0.6 mi 67.4 mi**

Follow Richardson Street east out of Douglas and goes past east Douglas interchange of I 25 onto frontage road. Driving on White River Formation and begin to see badlands exposures on both sides of road below radio tower hill. **2.3 mi 69.7 mi**

Frontage Road goes under Interstate 25. **4.1 mi 73.8 mi**

Turn Right beneath power line onto private Ranch boundary at locked gate. **0.3 mi 74.1 mi**

Follow two track road to overview of White River Formation Badlands. **0.7 mi 74.8 mi**

**Stop #2 (Day 2) White River Formation Badlands Fossil Collecting.**

42°42'07.41" N 105°16'14.61" W elev 5057 ft

| | | |
|---|---|---|
| Collect Oligocene (33 Ma) mammal and reptile fossils from Badlands | **1.0 mi** | **75.8 mi** |
| (Possible rest room stop at Mc Donald's or other Douglas, WY). | | |
| **Return to Casper and La Quinta Inn planned by 4:30 PM.** | **57.5 mi** | **133.3 mi** |

**END FIELD DAY**

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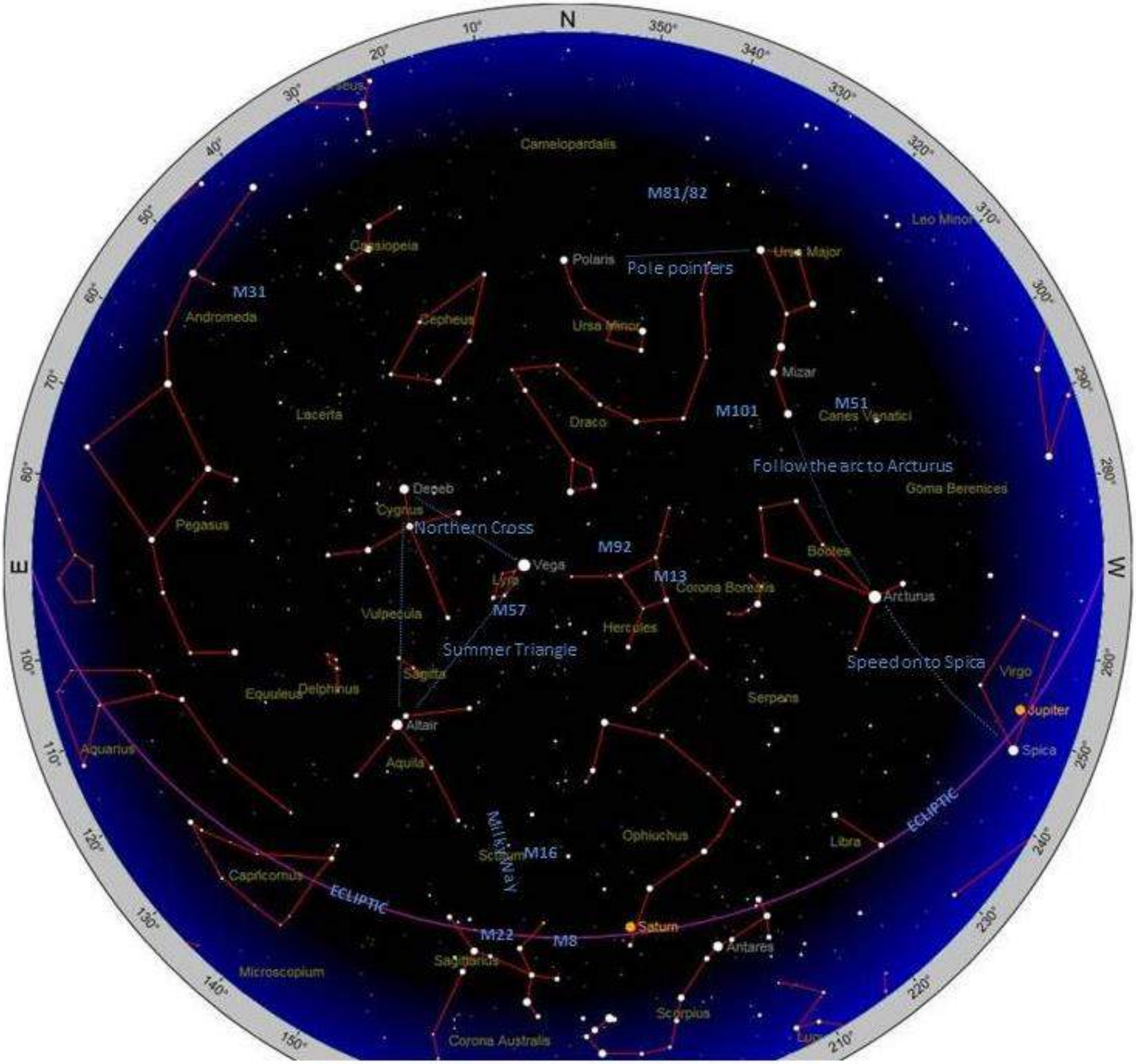
# SKY CHART CASPER, WY AUGUST 20 9 PM

**Recommended Smart Phone Apps STARMAP or SKY SAFARI**

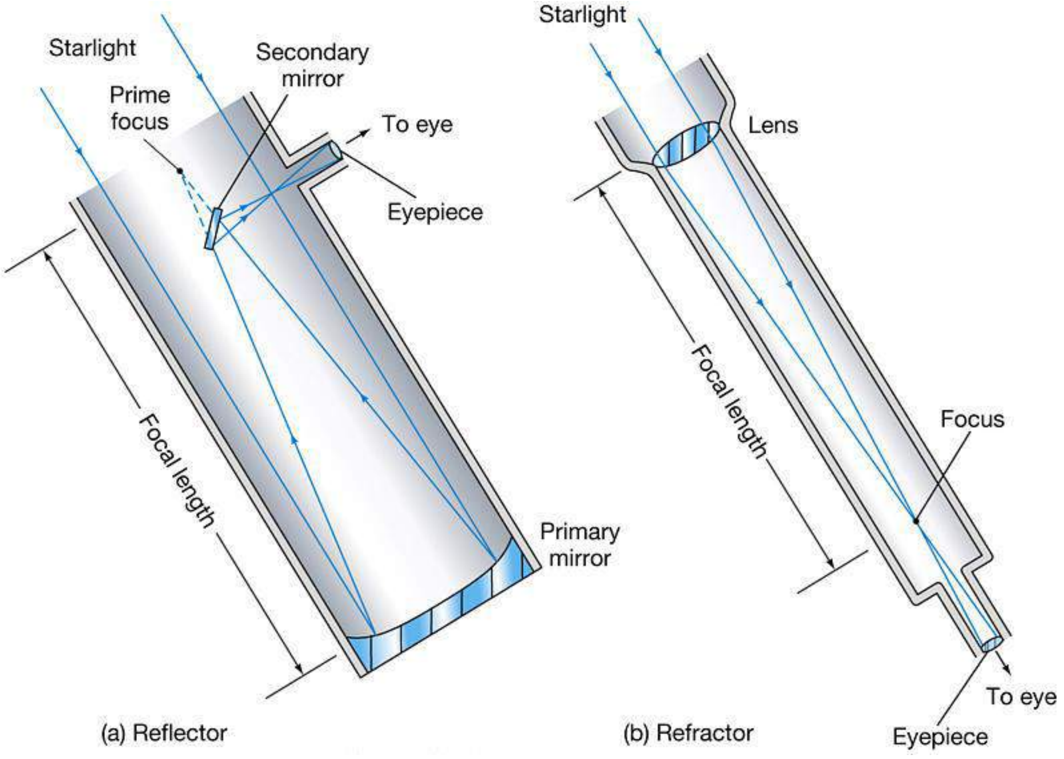


**SOUTH**

**<u>Caution on tripping in dark sky sites.</u> We will use red lights to preserve night vision.**

# Astronomy Equipment

## TELESCOPES: REFLECTOR vs REFRACTOR



(a) Reflector

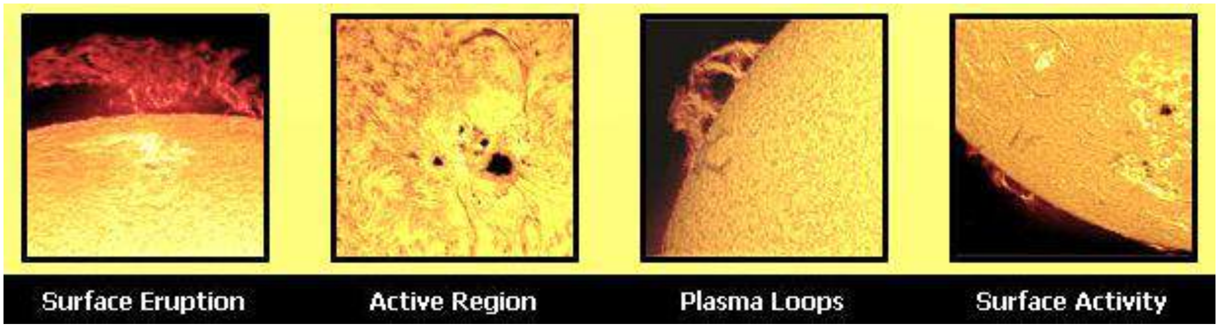
(b) Refractor

Dobsonian Reflector Telescope

80mm f/7.5 Apochromatic Refractor Telescope with white light solar filter.

**15x 70mm Astronomical Binoculars**

**Solar Telescope with H-Alpha Etelon Filter**

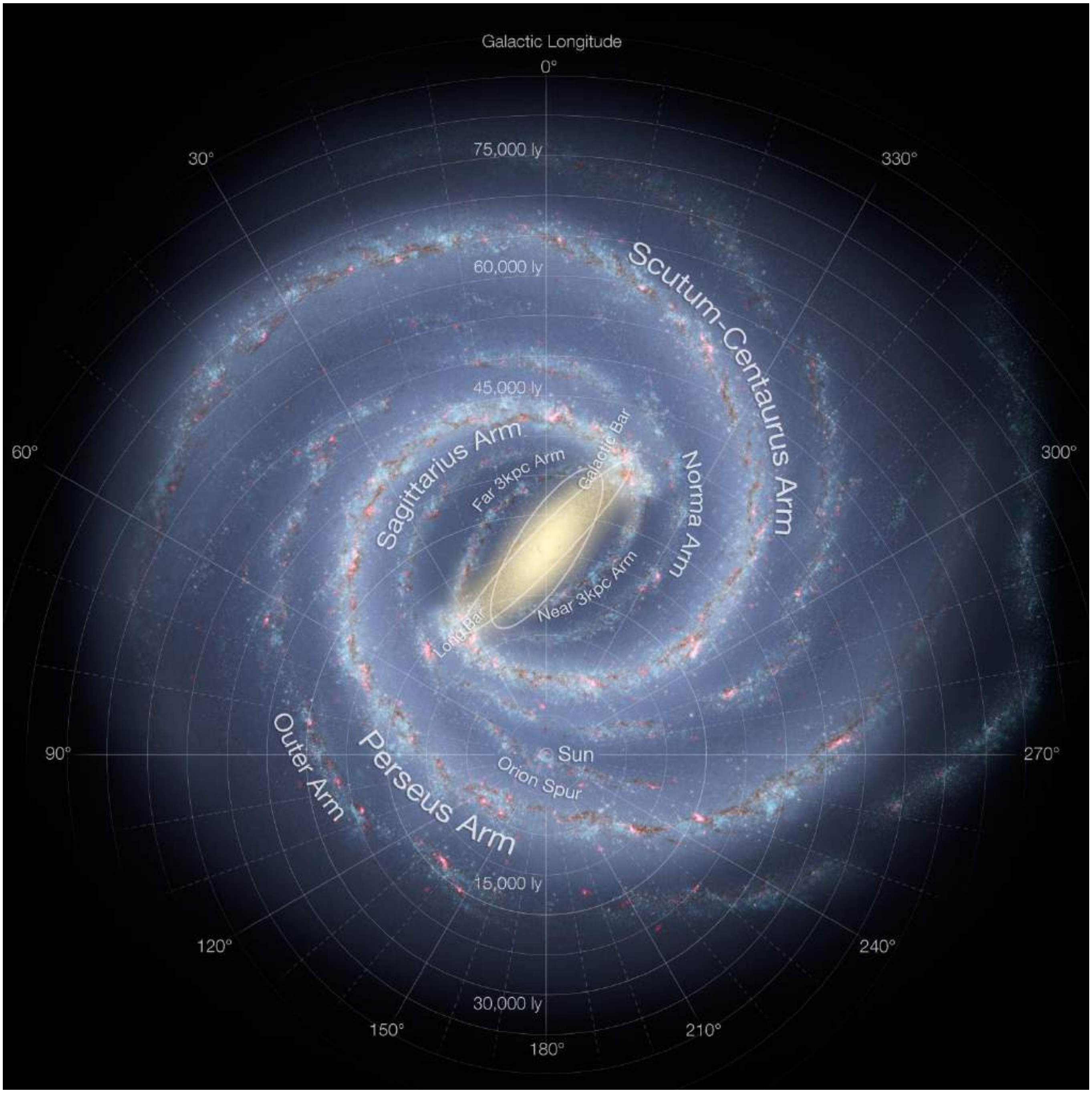


| **SUMMER SKY** | | | |
|---|---|---|---|
| **OBJECT / NAME** | **DESCRIPTION / CONSTELLATION** | **MAGNITUDE(s)** | **DISTANCE (LY)** |
| | | | |
| Polaris - Alpha UMi | Variable Double Star in Ursa Minor | 2.0 and 9.1 (18.2") | 430 |
| Mizar - Zeta UMa | Double Star in Ursa Major | 3.8 and 2.2 (14.6") | 86 |
| Andromeda Galaxy - M 31 | Spiral Galaxy in Andromeda | 3.3 (179') | 2.5 MLY |
| Whirlpool Galaxy - M 51 | Spiral Galaxy in Canes Venatici | 8.0 (13.8') | 28 MLY |
| Sunflower Galaxy - M 63 | Spiral Galaxy in Canes Venatici | 9 | 27 MLY |
| Messier 3 | Globular Cluster in Canes Venatici | 6.2 (18') | 33,000 |
| Messier 5 | Globular Cluster in Serpens | 5.6 (23') | 24,000 |
| Messier 52 | Open Cluster in Cassiopeia | 7.2 | 5000 |
| Alfirk - Beta Cep | Variable Double Star in Cepheus | 3.2 | 690 |
| Cat's Eye Nebula - NGC 6543 | Planetary Nebula in Draco | 9.8 (20") | 3262 |
| Hercules Cluster - M 13 | Globular Cluster in Hercules | 5.8 (20') | 23,000 |
| Messier 92 | Globular Cluster in Hercules | 6.4 (14') | 27,000 |
| Ring Nebula - M 57 | Planetary Nebula in Lyra | 8.8 (1.4') | 1400 |
| Messier 12 | Globular Cluster in Ophiuchus | 7.7 | 15,700 |
| Messier 10 | Globular Cluster in Ophiuchus | 6.4 | 14,300 |
| Messier 15 | Globular Cluster in Pegasus | 6.2 | 33,000 |
| Double Cluster - NGC 884 | Open Cluster in Perseus | 3.8 | 7600 |
| NGC 7000 N. America Nebula | Diffuse Nebula in Cygnus | 4.0 (120') | 2600 |
| Trifid Nebula - M 20 | Bright Nebula in Sagittarius | 6.3 (20') | 5200 |
| Omega Nebula - M 17 | Bright Nebula in Sagittarius | 6.0 (11') | 5500 |
| Lagoon Nebula - M 8 | Bright Nebula in Sagittarius | 6.0 (90') | 4100 |
| Messier 22 | Globular Cluster in Sagittarius | 5.1 (32') | 10,000 |
| Sagittarius Star Cloud - M 24 | Open Cluster in Sagittarius | 4.6 (90') | 10,000 |
| Antares - Alpha Sco | Double Star in Scorpius | 0.6 and 5.5 | 550 |
| Wild Duck Cluster - M 11 | Open Cluster in Scutum | 6.3 | 6200 |
| Eagle Nebula - M 16 | Bright Nebula in Serpens | 6 | 7000 |
| Pinwheel Galaxy - M 33 | Spiral Galaxy in Triangulum | 5.7 (70') | 2.4 MLY |
| Mizar - Zeta UMa | Double Star in Ursa Major | 2.2 and 3.8 (14.6") | 86 |
| Bode's Nebulae - M 81 | Spiral Galaxy in Ursa Major | 6.9 (27') | 11.8 MLY |
| Bode's Nebulae - M 82 | Spiral Galaxy in Ursa Major | 8.4 (11') | 12 MLY |
| Pinwheel Galaxy - M 101 | Spiral Galaxy in Ursa Major | 7.9 (24') | 23 MLY |
| Whirlpool Galaxy - M 51 | Spiral Galaxy in Canes Venatici | 8.0 (13.8') | 28 MLY |
| Formalhaut | Variable Double Star in Picses Aust | 1.2 and 6.6 (16') | 25 |

*Facing South around 10 PM August 20*

***Core of the Milky Way Galaxy***

# MAP OF OUR MILKY WAY GALAXY

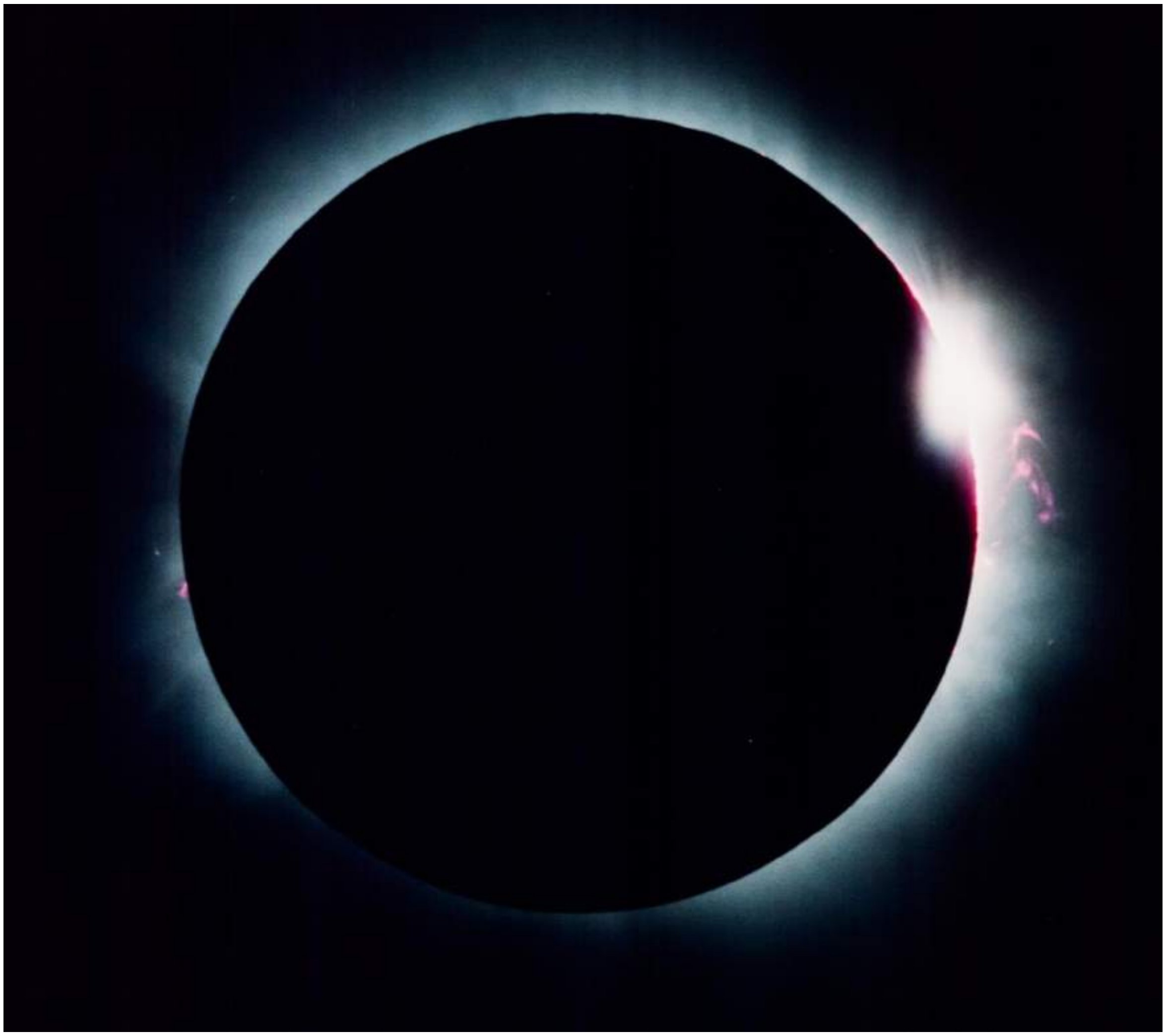


## M81 and M82 Galaxies in Ursa Major

## M13 Globular Cluster in Hercules

## M16 Star Forming Nebula in Serpens

# TOTAL SOLAR ECLIPSE



**Total Solar Eclipse Diamond Ring July 11, 1991 Baja California- Don Clarke**

# “Solar and Lunar Eclipses; Their Nature and Role in Human History and the Development of Science; from Harbingers of Doom, Cosmic Chaos, and Good Fortune to the Revolutionary Relativity of Einstein, Finding Extrasolar Planets and Beyond.”

By Karl S. Osvald
Casper Wyoming
May 16, 2017

Solar and Lunar eclipses are a periodic outcome of the dynamic orbital and tidal interplay of the Earth, Moon, and Sun system. This system’s history and nature has been an integral part of Earth history and will continue to be so for some time into the future. Although the history of relationship of human beings with eclipses predates our rise to consciousness as a species, intelligence and civilization, on the individual level there are few natural phenomena that continue to touch one as riveting as experiencing an eclipse, rather it be solar or lunar.

Eclipses can be held as rare events; there hasn’t been a cross-US total eclipse since 1918. They can also be frequent enough so as to be perceived as periodically impacting historic, economic, cultural, political, religious and scientific events. Every culture on the planet has some record of eclipse observation and utilization---rather it be for spiritual purposes or technological applications. Eclipses, in the modern sense, have and continue to fuel the ongoing observational efforts of a broad professional community of practice that ranges from time keepers, calendar makers, navigators, surveyors, and cartographers to geophysicists, geodesists, astronomers and planetary scientists. In the everyday sense, eclipses can still dramatically confront us personally with our place in the universe.

Through successive efforts at observation and analysis by a few thoughtful individuals over several millennia, eclipses have been transformed from a fearsome, periodic, omen or portent of cosmic events to a tourist attraction and scientific observational experiment. The pre-scientific success of the astrologers of ancient China and Babylon, the high priests of the Maya, Native Americans, and others show how different societies interpreted these periodic, dramatic, celestial events and their cultural importance. Ancient Greek philosophers first discovered eclipses' cause and used them to measure their world and the cosmos beyond more than 2,500 years ago. The global efforts of the newly emerging nation states of the past five hundred years for power and wealth drove the development of universal navigation and time keeping methods based on application of an understanding of eclipses in terms of the interplay of the orbital dynamics of the Sun, Moon and Earth. This understanding required maintenance of eclipse records and projected occurrence data of time and dates. National commitments to conduct continuous astronomical observation programs were now required and valued for time keeping, calendar maintenance, navigation, surveying, and cartography. Beneficial, related, outcomes included not only the rise and growth of global commerce and travel, but recognition of the importance of public, national, investments in science in general. European Victorian-era scientists mounted and competed in sensational globe spanning eclipse expeditions that established new achievements in science and human exploration.

Current-day physical scientists continue to use eclipses to test physical theory such as Einstein's general theory of relativity, while planetary scientists and astronomers use eclipse studies to understand our star, the Sun; evaluate risks posed by solar weather hazards; and to develop methodologies to search for planets beyond our Solar System.

In any case, eclipses continue to awe, inspire, and, yes, sometimes cause us to pause and take stock of the fact that we share a planet and a life with a wider cosmos.

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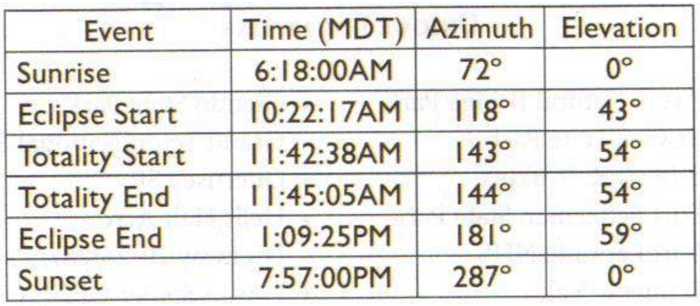
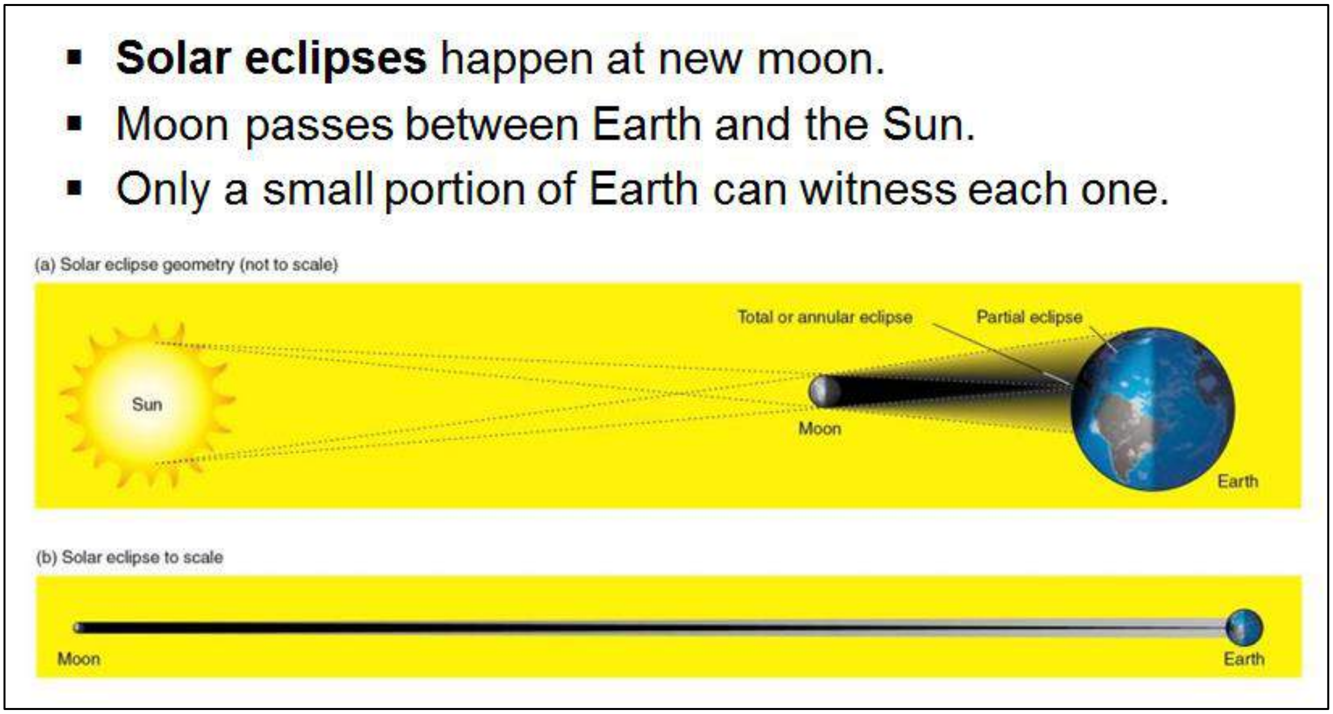
**Ft. Caspar Rd., Casper, WY, 42°50'19.59"N 106°22'26.83"W**

## Total Eclipse Venue: Isaak Walton Lodge
## Ft. Caspar Rd., Casper, WY, 42°50'19.59"N 106°22'26.83"W



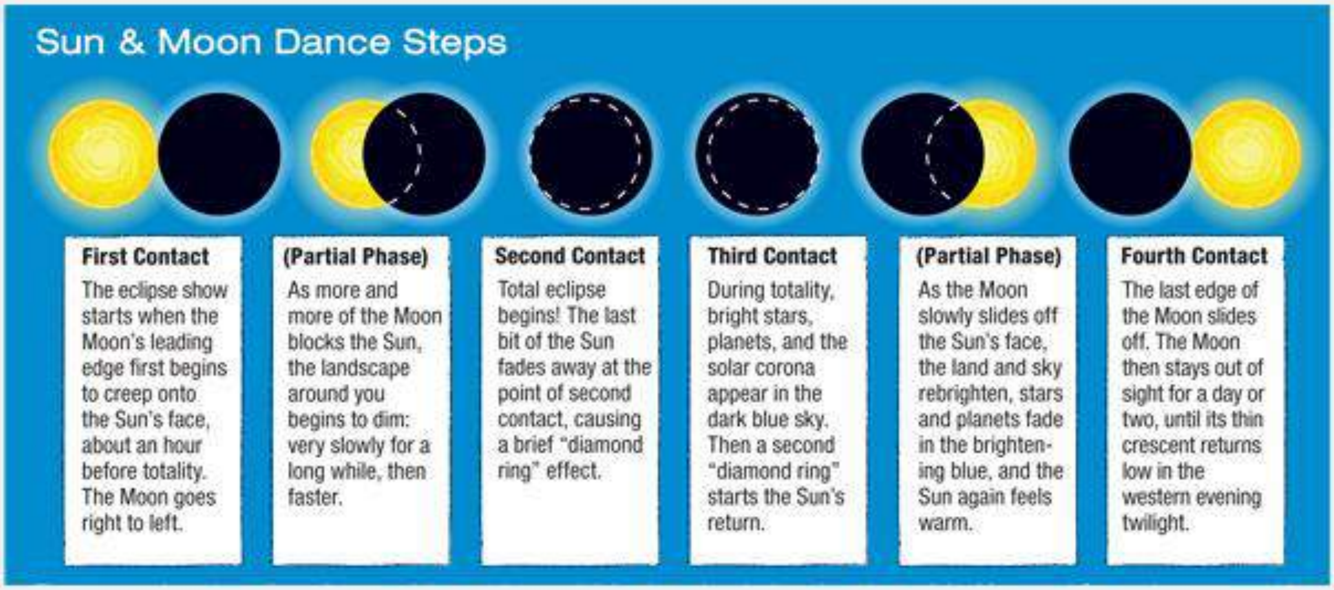
| Event | Time (MDT) | Azimuth | Elevation |
|---|---|---|---|
| Sunrise | 6:18:00AM | 72° | 0° |
| Eclipse Start | 10:22:17AM | 118° | 43° |
| Totality Start | 11:42:38AM | 143° | 54° |
| Totality End | 11:45:05AM | 144° | 54° |
| Eclipse End | 1:09:25PM | 181° | 59° |
| Sunset | 7:57:00PM | 287° | 0° |



- **Solar eclipses** happen at new moon.
- Moon passes between Earth and the Sun.
- Only a small portion of Earth can witness each one.

(a) Solar eclipse geometry (not to scale)

(b) Solar eclipse to scale



## Sun & Moon Dance Steps

**First Contact**
The eclipse show starts when the Moon's leading edge first begins to creep onto the Sun's face, about an hour before totality. The Moon goes right to left.

**(Partial Phase)**
As more and more of the Moon blocks the Sun, the landscape around you begins to dim: very slowly for a long while, then faster.

**Second Contact**
Total eclipse begins! The last bit of the Sun fades away at the point of second contact, causing a brief "diamond ring" effect.

**Third Contact**
During totality, bright stars, planets, and the solar corona appear in the dark blue sky. Then a second "diamond ring" starts the Sun's return.

**(Partial Phase)**
As the Moon slowly slides off the Sun's face, the land and sky rebrighten, stars and planets fade in the brightening blue, and the Sun again feels warm.

**Fourth Contact**
The last edge of the Moon slides off. The Moon then stays out of sight for a day or two, until its thin crescent returns low in the western evening twilight.

The stages of a solar eclipse, from partial to total to partial, begin and end when the edges of the Moon and Sun make contact with each other. This happens four times from start to finish.
S&T *illustration: Leah Tiscione/Gregg Dinderman*

# Ancient Explanations for Solar Eclipse

Ancient cultures tried to understand why the Sun temporarily vanished from the sky, so they came up with various reasons for what caused a solar eclipse. In many cultures, the legends surrounding solar eclipses involve mythical figures eating or stealing the Sun. Others interpreted the event as a sign of angry or quarreling gods.

**Hungry Demons, Thieving Dogs**

In Vietnam, people believed that a solar eclipse was caused by a giant frog devouring the Sun, while Norse cultures blamed wolves for eating the Sun. In ancient China, a celestial dragon was thought to lunch on the Sun, causing a solar eclipse. In fact, the Chinese word of an eclipse, *chih* or *shih*, means *to eat*.

In Hindu mythology, Rahu is known for swallowing the sun and causing eclipses.

A popular **MODERN** misconception is that solar eclipses can be a danger to pregnant women and their unborn children. In many cultures, young children and pregnant women are asked to stay indoors during a solar eclipse.

# The Experience of Totality

*In rating natural wonders, on a scale of 1 to 10, a total eclipse of the Sun is a million.*

An observer who has seen 27 total eclipses[1]

First contact. A tiny nick appears on the western side of the Sun.[2] The eye detects no difference in the amount of sunlight. Nothing but that nick portends anything out of the ordinary. But as the nick becomes a gouge in the face of the Sun, a sense of anticipation begins. This will be no ordinary day.

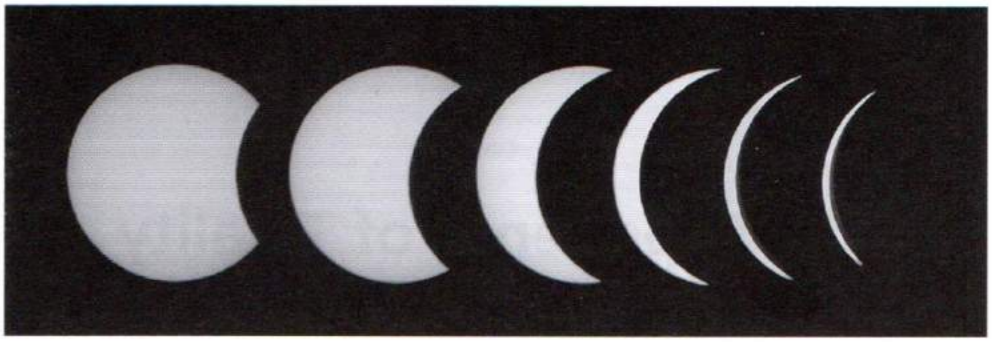
Still, things proceed leisurely for the first half hour or so, until the Sun is more than half covered. Now, gradually at first, then faster and faster, extraordinary things begin to happen. The sky is still bright, but the blue is a little duller. On the ground around you the light is beginning to dim. Over the next 10 to 15 minutes, the landscape takes on a steely gray metallic cast.

As the minutes pass, the pace quickens. With about a quarter of an hour left until totality, the western sky is now darker than the east, regardless of where the Sun is in the sky. The shadow of the Moon is approaching. Even if you have never seen a total eclipse of the Sun before, you know that something amazing is going to happen, is happening now—and that it is beyond normal human experience.

Less than 15 minutes until totality. The Sun, a narrowing crescent, is still fiercely bright, but the blueness of the sky has deepened into blue-gray or violet. The darkness of the sky begins to close in around the Sun. The Sun does not fill the heavens with brightness anymore.

Five minutes to totality. The darkness in the west is very noticeable and gathering strength—a dark, amorphous form rising upward and spreading out along the western horizon. It builds like a massive storm, but in utter silence, with no rumble of distant thunder. And now the darkness begins to float up above the horizon, revealing a yellow or orange twilight beneath. You are already seeing through the Moon's narrow shadow to the resurgent sunlight beyond.

The acceleration of events intensifies. The crescent Sun is now a blazing white sliver, like a welder's torch. The darkening sky continues to close in around the Sun, faster, engulfing it.



Partial phases of the total solar eclipse of March 29, 2006, from Jalu, Libya. [Nikon D200 DSLR, Sigma 170–500 mm at 500 mm, f/11, 1/500 s, ISO 200, Thousand Oaks Type 3 solar filter. ©2006 Patricia Totten Espenak]

Minutes have become seconds. A ghostly round silhouette looms into view. It is the dark limb of the Moon, framed by a white opalescent glow that creates a halo around the darkened Sun. The corona, the most striking and unexpected of all the features of a total eclipse, is emerging. At one edge of the Moon the brilliant solar crescent remains. Together they appear as a celestial diamond ring.

Suddenly, the ends of the bare sliver of the Sun break into individual points of intense white light—Baily's beads—the last rays of sunlight passing through the deepest lunar valleys. The beads flicker, each lasting but an instant and vanishing as new ones form. And now there is just one left. It glows for a moment, then fades as if it were sucked into an abyss.

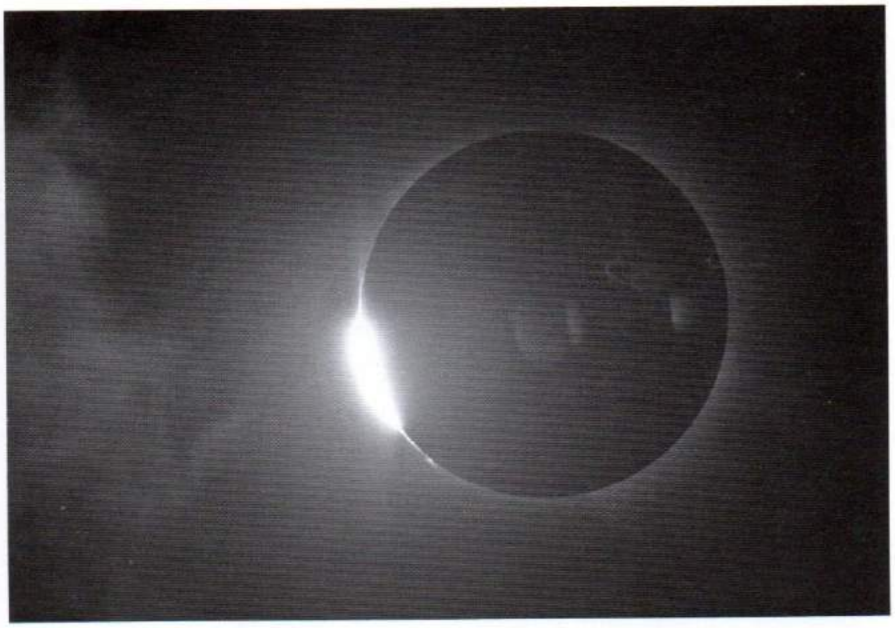
Totality.

Where the Sun once stood, there is a black disk in the sky, outlined by the soft, pearly white glow of the corona, about the brightness of a full moon. Small but vibrant reddish features stand at the eastern rim of the Moon's disk, contrasting vividly with the white of the corona and the black where the Sun is hidden. These are the prominences, giant clouds of hot gas in the Sun's lower atmosphere. They are always a surprise, each unique in shape and size, different yesterday and tomorrow from what they are at this special moment.

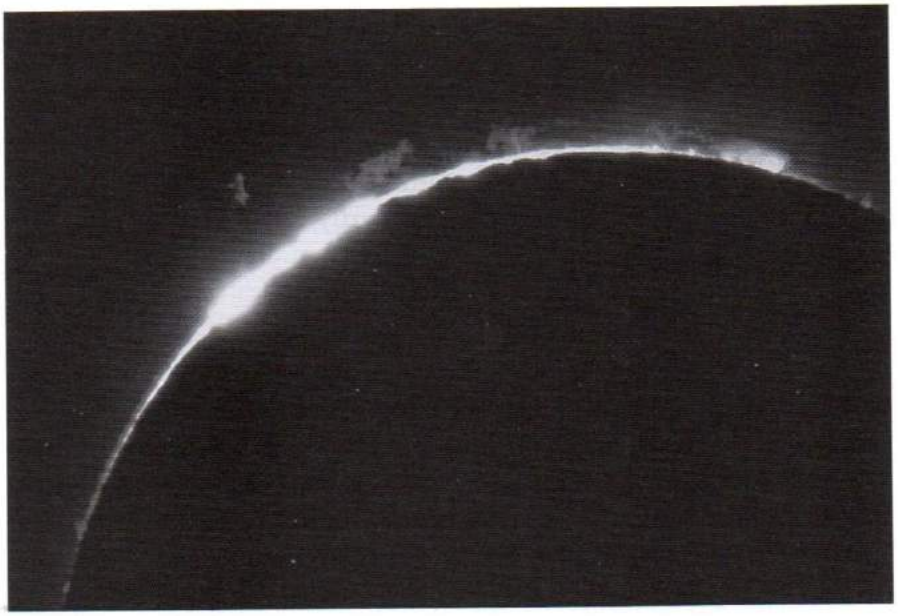
You are standing in the shadow of the Moon.

It is dark enough to see Venus and Mercury and whichever of the brightest planets and stars happen to be close to the Sun's position and above the horizon. But it is not the dark of night. Looking across the landscape at the horizon in all directions, you see beyond the shadow to where the eclipse is not total, an eerie twilight of orange and yellow. From this light beyond the darkness that envelops you comes an inexorable sense that time is limited.

Now, at the midpoint in totality, the corona stands out most clearly, its shape and extent never quite the same from one eclipse to another. And only the eye can do the corona justice, its special pattern of faint wisps and spikes on this day never seen before and never to be seen again.

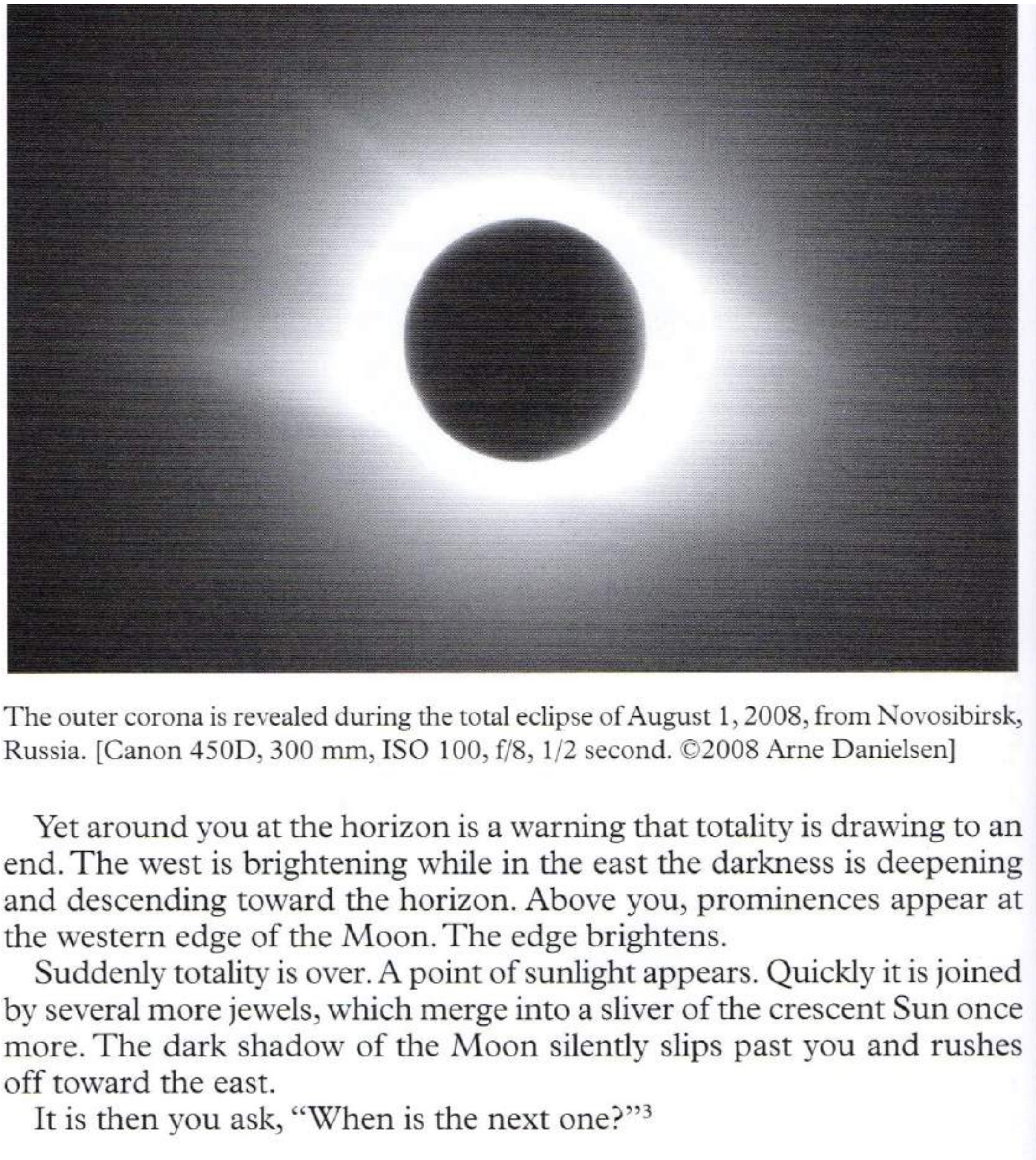


Diamond ring effect at the total solar eclipse of July 11, 2010, from Easter Island. [Nikon D700, Borg 100ED & 2x teleconverter, fl = 1280 mm, ISO 800, f/12.8 at 1/4000 second. ©2010 Dave Kodama]



Baily's beads are seen amid a forest of prominences during the total solar eclipse of August 11, 1999, from Lake Hazar, Turkey. [Pentax SLR, 94 mm Brandon refractor, f/30, 1/125 s, Ektachrome V100 film pushed to ISO 200. ©1999 Greg Babcock]

The Experience of Totality



The outer corona is revealed during the total eclipse of August 1, 2008, from Novosibirsk, Russia. [Canon 450D, 300 mm, ISO 100, f/8, 1/2 second. ©2008 Arne Danielsen]

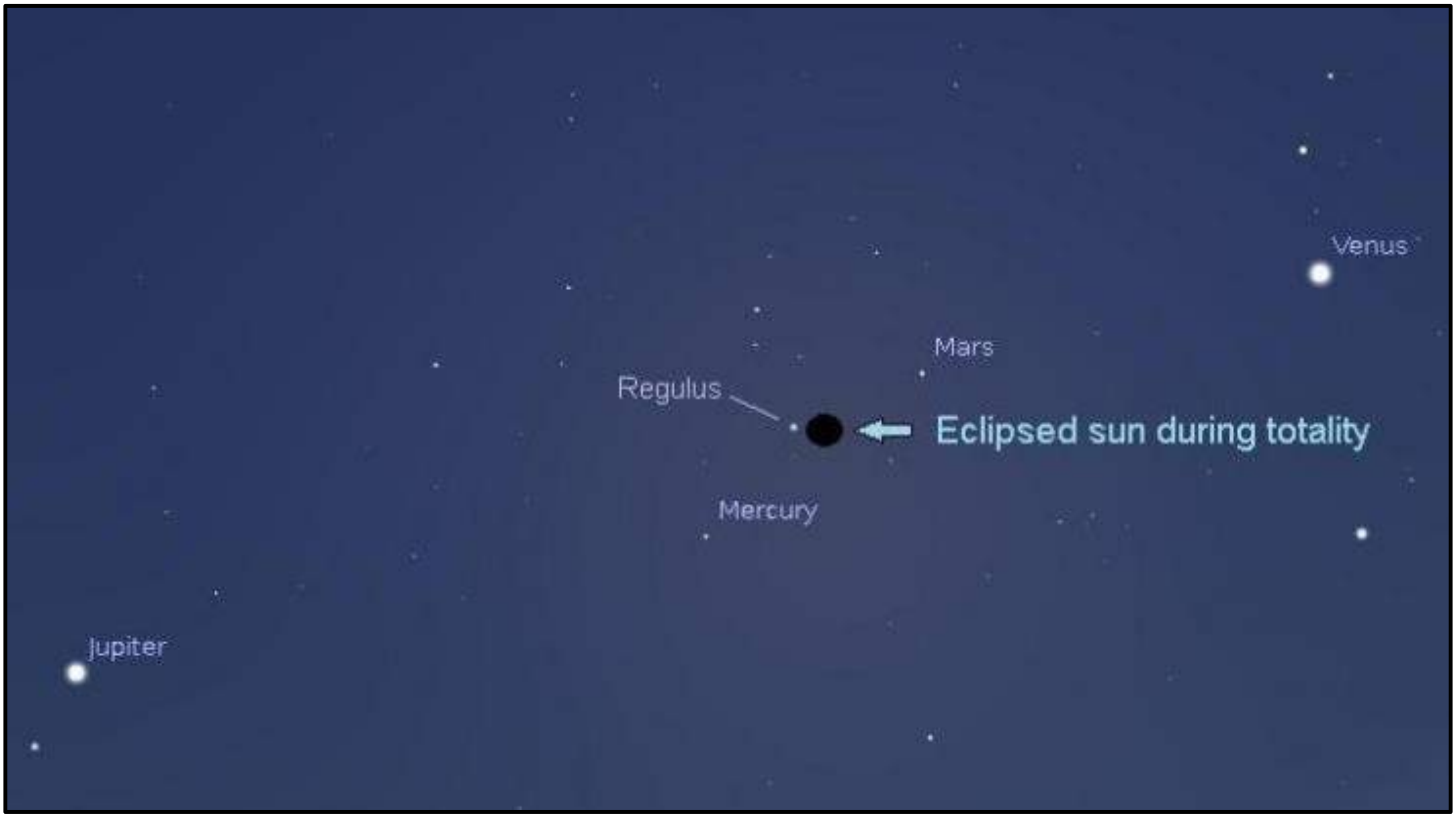
Yet around you at the horizon is a warning that totality is drawing to an end. The west is brightening while in the east the darkness is deepening and descending toward the horizon. Above you, prominences appear at the western edge of the Moon. The edge brightens.

Suddenly totality is over. A point of sunlight appears. Quickly it is joined by several more jewels, which merge into a sliver of the crescent Sun once more. The dark shadow of the Moon silently slips past you and rushes off toward the east.

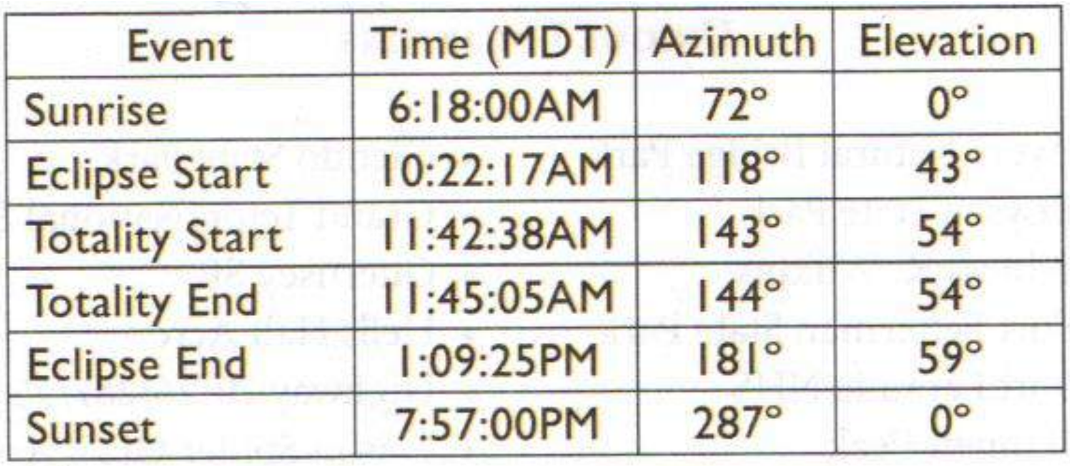
It is then you ask, "When is the next one?"[3]

**Littmann, Mark and Fred Espenak. 2017. Totality; the Great American Eclipses of 2017 and 2014. Oxford University Press. New York. NY.**

# Positions of four visible planets during Totality in Aug 21, 2017 Eclipse



Total Eclipse Duration: 2 minutes 27 seconds



| Event | Time (MDT) | Azimuth | Elevation |
|---|---|---|---|
| Sunrise | 6:18:00AM | 72° | 0° |
| Eclipse Start | 10:22:17AM | 118° | 43° |
| Totality Start | 11:42:38AM | 143° | 54° |
| Totality End | 11:45:05AM | 144° | 54° |
| Eclipse End | 1:09:25PM | 181° | 59° |
| Sunset | 7:57:00PM | 287° | 0° |

## Eclipses in Casper, Wyoming, USA

Max View in Casper

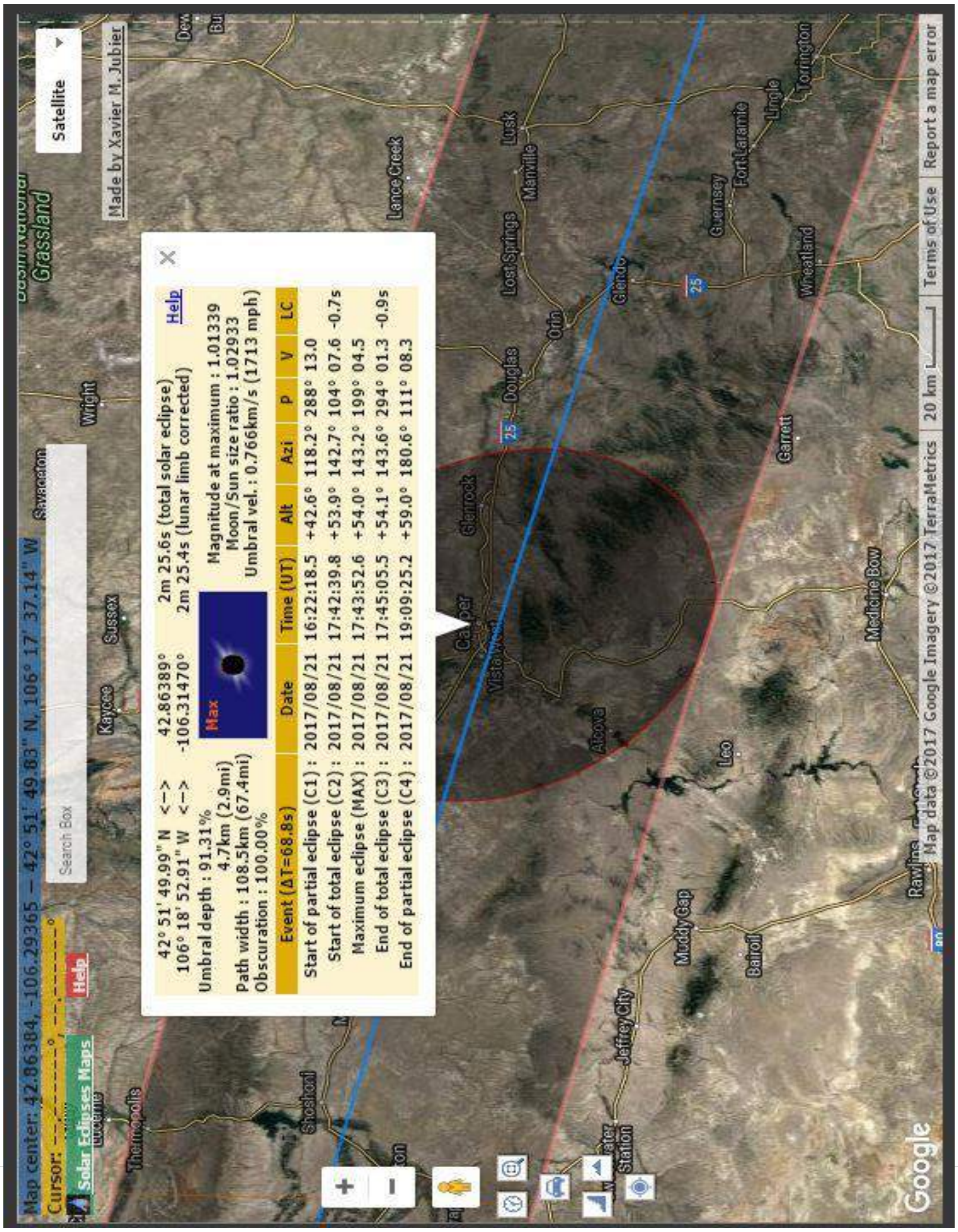
Monday, August 21, 2017
at 11:43 am

Global Type: Total Solar Eclipse
Casper: Total Solar Eclipse

Begins: Mon, Aug 21, 2017 at 10:22 am Countdown
Maximum: Mon, Aug 21, 2017 at 11:43 am
Ends: Mon, Aug 21, 2017 at 1:09 pm

Duration: 2 hours, 47 minutes
Totality: 2 minutes, 27 seconds
Magnitude: 1.01

Casper UTC -6 Hours



Map center: 42.86384, -106.29365 — 42° 51' 49.83" N, 106° 17' 37.14" W

42° 51' 49.99" N <-> 42.86389°
106° 18' 52.91" W <-> -106.31470°
2m 25.6s (total solar eclipse)
2m 25.4s (lunar limb corrected)
Umbral depth : 91.31%
4.7km (2.9mi)
Path width : 108.5km (67.4mi)
Obscuration : 100.00%
Magnitude at maximum : 1.01339
Moon/Sun size ratio : 1.02933
Umbral vel. : 0.766km/s (1713 mph)

| Event (ΔT=68.8s) | Date | Time (UT) | Alt | Azi | P | V | LC |
|---|---|---|---|---|---|---|---|
| Start of partial eclipse (C1) : | 2017/08/21 | 16:22:18.5 | +42.6° | 118.2° | 288° | 13.0 | |
| Start of total eclipse (C2) : | 2017/08/21 | 17:42:39.8 | +53.9° | 142.7° | 104° | 07.6 | -0.7s |
| Maximum eclipse (MAX) : | 2017/08/21 | 17:43:52.6 | +54.0° | 143.2° | 199° | 04.5 | |
| End of total eclipse (C3) : | 2017/08/21 | 17:45:05.5 | +54.1° | 143.6° | 294° | 01.3 | -0.9s |
| End of partial eclipse (C4) : | 2017/08/21 | 19:09:25.2 | +59.0° | 180.6° | 111° | 08.3 | |

National Aeronautics and Space Administration

# EXPERIENCE THE 2017 ECLIPSE ACROSS AMERICA

## *THROUGH THE EYES OF NASA* ▸ http://eclipse2017.nasa.gov

## MONDAY • AUGUST 21, 2017


Credit: S. Habbal, M. Druckmüller and P. Aniol


Credit: Marla Hladiuk

### WHAT IS A SOLAR ECLIPSE?

A solar eclipse happens when the moon casts a shadow on Earth, fully or partially blocking the sun's light in some areas.

Observers within the path of totality will be able to see the sun's corona (weather permitting), like in the images above and left. Observers outside this path will see a partial eclipse.

### THE NEXT ECLIPSE

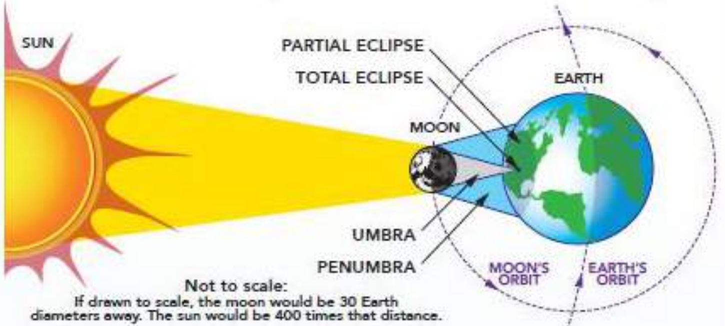
After the 2017 solar eclipse, the next total solar eclipse visible over the continental United States will be on **April 8, 2024.**


Credit: International Space Station

This photo taken from the International Space Station shows the moon's umbral, or inner, shadow during the total solar eclipse of March 29, 2006.

### TOTAL SOLAR ECLIPSE: Monday • August 21, 2017

This will be the first total solar eclipse visible in the continental United States in 38 years.



Not to scale:
If drawn to scale, the moon would be 30 Earth diameters away. The sun would be 400 times that distance.


Credit: Rick Fienberg, TravelQuest International and Wilderness Travel

In this series of stills from 2013, the eclipse sequence runs from right to left. The center image shows totality; on either side are the 2nd contact (right) and 3rd contact (left) diamond rings that mark the beginning and end of totality respectively.

### WHERE TO WATCH

Find a nice, clear spot with a good view of the sky.

### HOW TO WATCH

You can see the sun and the eclipse with special eclipse glasses. NEVER look directly at the sun without appropriate eyewear. More: *http://eclipse2017.nasa.gov/safety*

### HOW LONG WILL IT LAST

The total eclipse, when the sun is completely blocked by the moon, will last up to 2 minutes and 40 seconds, depending on your location.


Credit: NASA's Scientific Visualization Studio

This map shows the path of the moon's umbral shadow—in which the sun will be completely obscured by the moon—during the total solar eclipse of August 21, 2017. The lunar shadow enters the United States near Lincoln City, Oregon, at 9:05 a.m. PDT. Totality begins in Lincoln City, Oregon, at 10:16 a.m. PDT. The total eclipse will end in Charleston, South Carolina, at 2:48 p.m. EDT. The lunar shadow leaves the United States at 4:09 p.m. EDT. Outside this path, a partial solar eclipse will be visible throughout the continental U.S., and this map shows the fraction of the sun's area covered by the moon outside the path of totality.

# EYE SAFETY DURING AN ECLIPSE

It's NEVER safe to look directly at the sun, except when the sun is completely blocked during the period of a total eclipse known as TOTALITY.

1

## PARTIAL ECLIPSE • GLASSES ON

The eclipse begins when the sun's disk is partially blocked by the moon. This partial eclipse phase can last over an hour.

2

## BAILY'S BEADS • GLASSES ON

As totality approaches, only the low-lying valleys on the moon's edge allow sunlight through, forming bright spots of light called Baily's Beads.

3

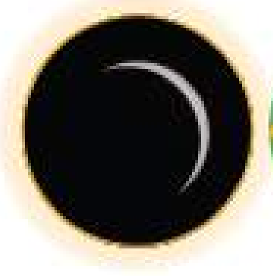
## DIAMOND RING • GLASSES ON

The last of the sunlight streaming through the moon's valleys creates a single bright flash of light on the side of the moon. This is known as the diamond ring effect, and it marks the last few seconds before totality begins.

4

## TOTALITY • GLASSES OFF

Once the diamond ring disappears and the moon completely covers the entire disk of the sun, you may safely look at the eclipse without a solar filter. Be careful to protect your eyes again before the end of totality—the total eclipse may last less than a minute in some locations.



5

## FINAL STAGES • GLASSES ON

A crescent will begin to grow on the opposite side of the sun from where the Baily's Beads shone at the beginning. This crescent is the lower atmosphere of the sun, beginning to peek out from behind the moon and it is your signal to stop looking directly at the eclipse. Make sure you have safety glasses back on—or are otherwise watching the eclipse through a safe, indirect method—before the first flash of sunlight appears around the edges of the moon.

Images 1 and 3-5 Credit: Rick Fienberg, TravelQuest International and Wilderness Travel
Image 2 Credit: Arne Danielson

# Eclipse Exposures

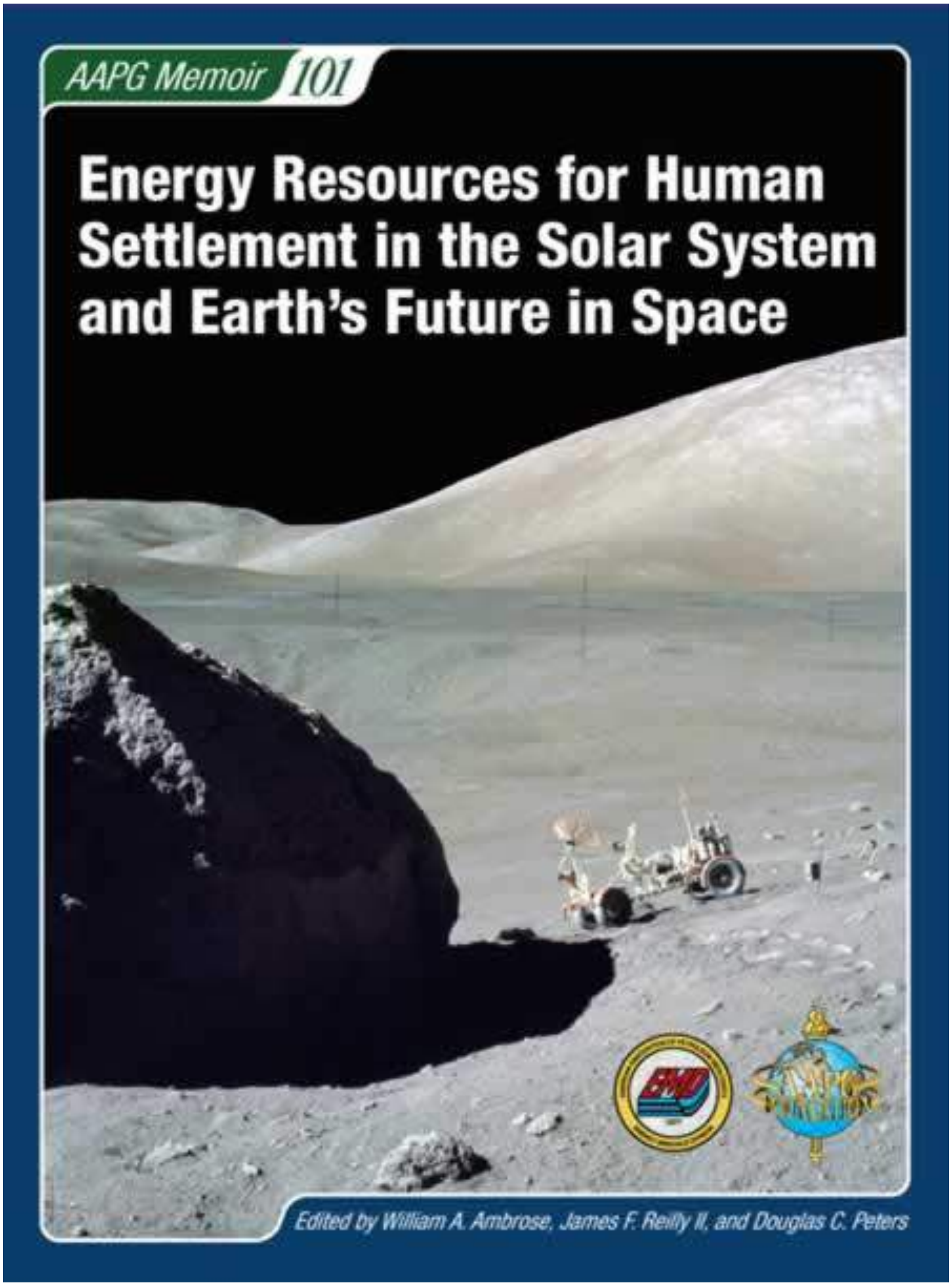
The exposures in the table below are in seconds for totality with no filter with the Sun reasonably high in a clear sky.

**Instructions:**

- Pick your ISO from the column at top left.
- Then read across on that line to your f/stop.
- Then read down for shutter speed.

| Eclipse Exposure Table | | | | | | |
|---|---|---|---|---|---|---|
| **ISO** | **F/Stop** | | | | | |
| 100 | 2.8 | 4 | 5.6 | 8 | 11 | 16 |
| 200 | 4 | 5.6 | 8 | 11 | 16 | 22 |
| 400 | 5.6 | 8 | 11 | 16 | 22 | 32 |
| 800 | 8 | 11 | 16 | 22 | 32 | 45 |
| 1600 | 11 | 16 | 22 | 32 | 45 | 64 |
| **Phenomenon** | **Shutter Speed** | | | | | |
| Partial Phases ND5 | 1/4000 | 1/2000 | 1/1000 | 1/500 | 1/250 | 1/125 |
| Diamond Ring | 1/500 | 1/250 | 1/125 | 1/60 | 1/30 | 1/15 |
| Baily's Beads | NA | NA | 1/8000 | 1/4000 | 1/2000 | 1/1000 |
| Chromosphere | NA | 1/8000 | 1/4000 | 1/2000 | 1/1000 | 1/500 |
| Prominences | 1/8000 | 1/4000 | 1/2000 | 1/1000 | 1/500 | 1/250 |
| Corona 0.1 Rs[1] | 1/2000 | 1/1000 | 1/500 | 1/250 | 1/125 | 1/60 |
| Corona 0.2 Rs | 1/500 | 1/250 | 1/125 | 1/60 | 1/30 | 1/15 |
| Corona 0.5 Rs | 1/125 | 1/60 | 1/30 | 1/15 | 1/8 | 1/4 |
| Corona 1.0 Rs | 1/30 | 1/15 | 1/8 | 1/4 | 1/2 | 1 |
| Corona 2.0 Rs | 1/15 | 1/8 | 1/4 | 1/2 | 1 | 2 |
| Corona 4.0 Rs | 1/4 | 1/0 | 1 | 2 | 4 | 8 |
| Corona 8.0 Rs | 1 | 2 | 4 | 8 | 16 | 32 |
| Earthshine | 1 | 2 | 4 | 8 | 16 | 32 |
| Sky Background Mag 15 - 16 | 4 - 10 | 8 - 20 | 16 - 40 | 30 - 80 | 60 - 160 | 120 - 360 |

# AT THE AAPG BOOK STORE



**"All long-range programs for human exploration and settlement of the solar system recognize the vital role that extraterrestrial energy and mineral resources must play in support of human habitation of near Earth Space and the Moon, Mars, and the Asteroids." Produced in collaboration with the AAPG Energy Minerals Division and the AAPG Astrogeology Committee.**

**Memoir 101: All 9 Chapters**

# Cluster of Five Small Pennsylvanian Meteorite Impact Craters on Sheep Mountain near Douglas, Wyoming

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University of Wyoming
Laramie, WY 82071

## ABSTRACT

A cluster of five small meteorite craters has been identified on the north flank of Sheep Mountain, 8 miles south-southwest of Douglas, Wyoming. The impacts occurred approximately 300 million years ago because they deformed the strata that now comprise the upper quartzite member in the Pennsylvanian Casper Formation and were subsequently buried. The cluster of craters represents an object that broke into at least five pieces before impact. The preserved deformed zone around the largest crater measures about 370 feet in diameter. The primary evidence supporting an impact origin for the craters includes: (1) a crater geometry characteristic of small impacts and (2) shocked quartz. No fragments of the meteorite are preserved at the site and no shatter cones have been found in the deformed rocks.

## INTRODUCTION

Spelman (1959) observed several circular depressions, including Crater 1 treated here, in the upper quartzite member of the Casper Formation on the northeastern flank of Sheep Mountain anticline. He did not interpret their origins. George (1994, personal communication) independently discovered Crater 1, concluded that it appeared to be of impact origin, and reported its existence to Peter Huntoon at the University of Wyoming. We undertook an inventory of the circular features on Sheep Mountain and concluded that five were of probable impact origin.

## PROCEDURES

An inventory was made to locate the circular features on Sheep Mountain with the objective to differentiate those of probable impact origin from breccia pipes, paleo-sinkholes, landslides and eroded depressions. If the feature had upturned rims, ring faults and/or highly deformed core rocks, it was considered to be a potential impact. It was then located on low-altitude aerial photography and its position transferred to a topographic map. The suspected craters were numbered from largest to smallest.

Next, detailed site characterization of the suspected craters was undertaken. The planimetric and cross-sectional forms of the craters were delineated, and the diameters measured. The radial position of all ring structures were measured, and the rings were classified as to whether they were interior-facing crater walls, the most elevated crest of the crater rims or low-angle thrusts. The cross-sectional form of the craters were documented including the vertical shapes of the faults, stratigraphic thickening within the displaced rock comprising the crater rims, and stratigraphic dips in the profile.

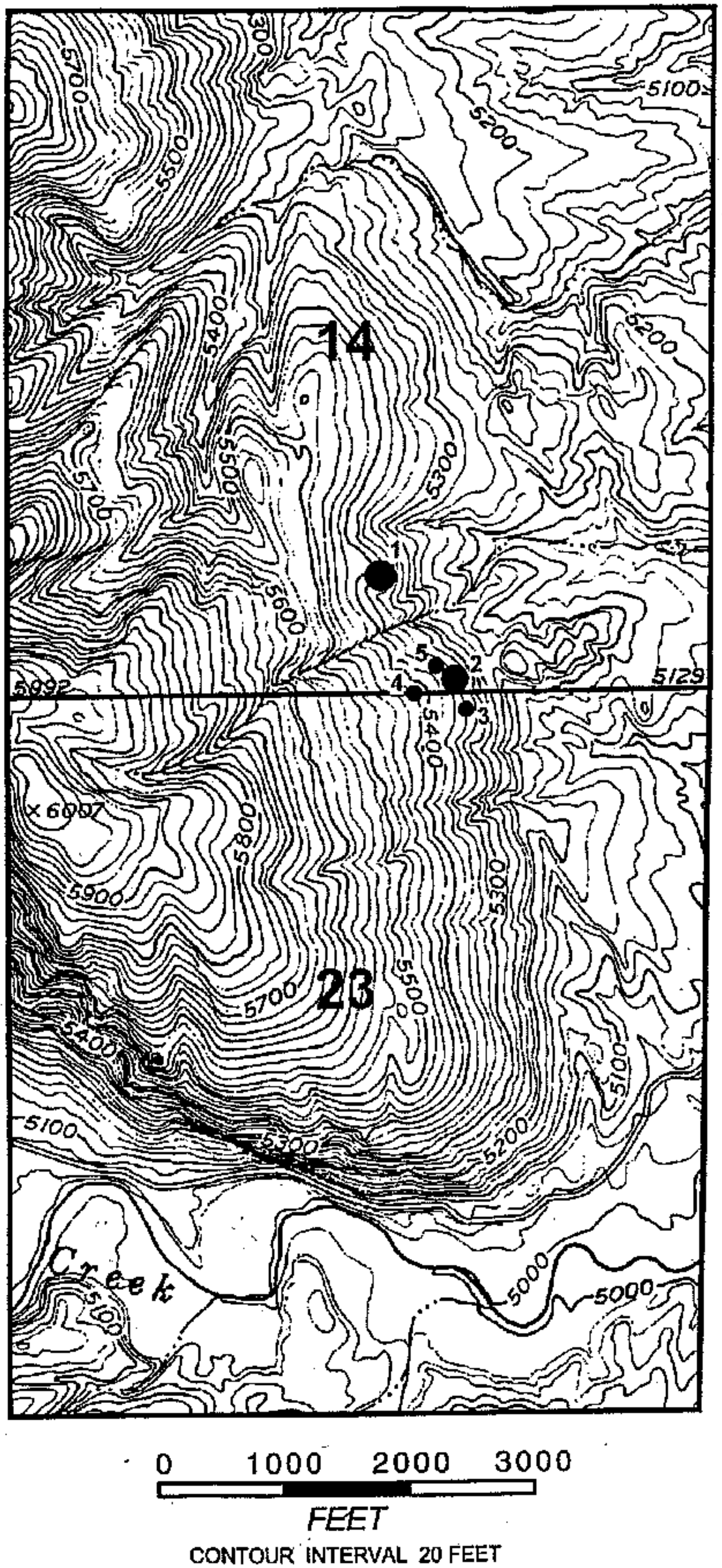


**Figure 1.** Location and numbers of the small impact craters on Sheep Mountain, 8 miles south-southwest of Douglas, Wyoming. The area shown encompasses sections 14 and 23 of T31N, R72W. Topographic base from Chalk Buttes, Wyoming, 7.5 minute topographic quadrangle.

**Table 1. Crater size and radii to key structural elements in feet for the impact craters on Sheep Mountain near Douglas, Wyoming.** Crater numbers correspond to Figure 1.

| Crater | Radius | Radius to Rim | Radius to First Ring Fault | Radius to Second Ring Fault |
|---|---|---|---|---|
| 1 | 185 | 100 | 115 | 185 |
| 2 | 145 | 58 | 67 | 145 |
| 3 | 90 | 69 | 90 | |
| 4 | 80 | 52 | 80 | |
| 5 | 49 | 43 | 49 | |

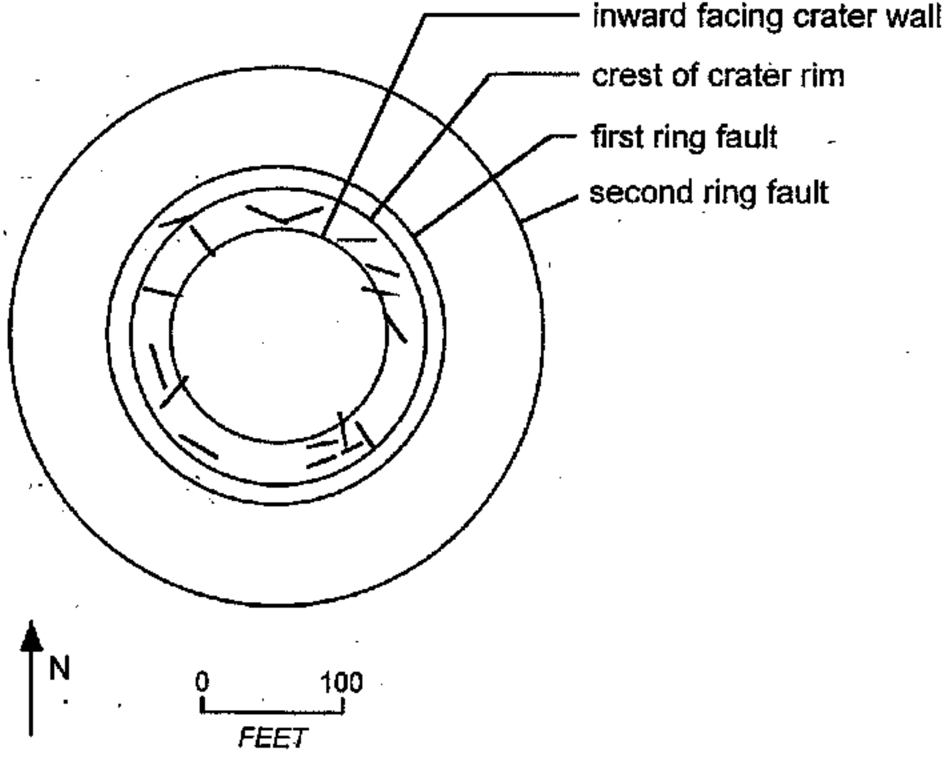


**Figure 2. Idealized sketch map of Crater 1 showing the location of various ring features, and the locations and orientations of the maximum principal stresses (short line segments) deduced from conjugate shears.**

Conjugate shear fractures in the rocks comprising the upturned rims were mapped. This was undertaken in order to determine the maximum principal stress orientations so that strain patterns could be deduced.

Rock samples were collected in order to perform thin section analyses. The locations of the samples were recorded. Rock samples were collected from various radial positions within the deformed zones comprising the craters as well as from undeformed country rock in nearby outcrops. The purpose of collecting these samples was to examine them for cataclasis, flowage and the possible presence of shocked quartz using standard laboratory thin section analytical techniques.

Photographs were taken to: (1) show the setting of the craters and (2) record visible structures such as ring faults, brecciation and flowage.

## DATA ANALYSIS

Five craters were located on the northeast dipping flank of the Sheep Mountain anticline. The impacts occur in the upper quartzite member of the Pennsylvanian Casper Formation which has been stripped of overlying sediments by erosion. The craters are deeply eroded so that no strata younger than the Casper Formation remains in them. Some of the crater rims have been breached by erosion and the floors of some of the craters have been partially dissected. Fortunately, what remains is well preserved due to the hardness of the Casper quartzite. Missing are the rocks that buried the craters, shatter cones, melt rocks and meteorite fragments.

The locations of the craters are shown on Figure 1. The radii of the craters, and position and type of the ring structures appear in Table 1. The crater radii range from 49 to 185 feet. Each crater has an obvious rim and at least one ring fault. Some exhibit two ring faults.

Cross sectional sketches of each crater are shown on Figure 2. Commonalities include stratigraphic thickening within the detached plates with the thickest sections occurring directly under the crests of the rims. Stratigraphic dips that are both inward and outward away from the crests. One or two low-angle thrust faults that crop out radially outside the rim that served to move material outward (Shoemaker, 1963).

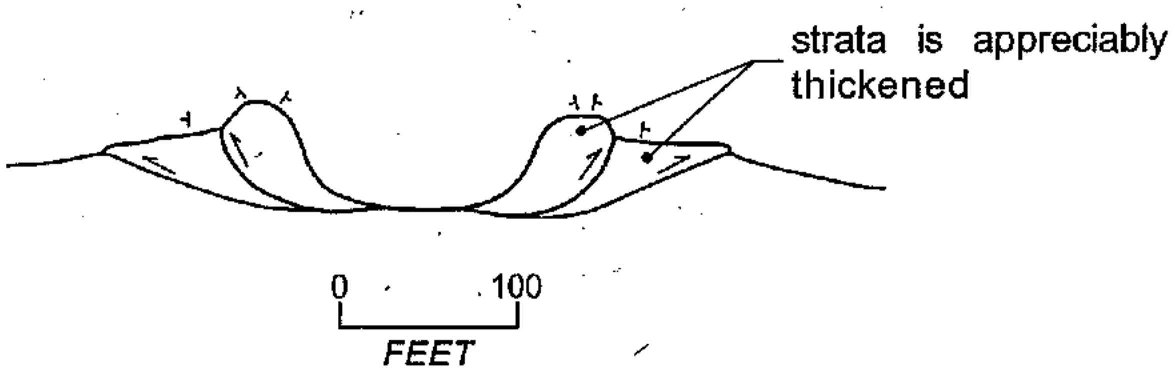


**Figure 3. Simplified structural profile through Crater 1. Dip symbols show the attitude of the strata at the surface in the displaced rings. The vertical scale is exaggerated.**

The rocks in the floors of Crater 1 are exposed and some are locally brecciated. In addition, outcrops in Crater 1 and other craters contain dikes that exhibit flow-banded, recemented rock.

A plan view of crater 1 appears on Figure 3 which shows the locations and orientations of the maximum principal stresses as deduced from conjugate shears fractures. The maximum principal stress tensors were interpreted from the conjugate shears by passing the tensor through the acute angle. Two organized populations of maximum principal stresses are present along with others with random orientations. The organized populations are oriented radial and concentric to the crater. We interpret the radially-oriented tensors as originating during the excavation flow stage (Melosh, 1989) as the crater opened. Those parallel to the circumference probably developed during the gravity modification stage (Melosh, 1989) as the crater collapsed and the mobile plates above the ring thrust faults moved inward.

The thin sections made from the samples listed in Table 2 were particularly definitive. Samples from the crater interiors revealed pervasive cataclasis of quartz grains, the presence of shocked quartz, and convoluted laminations indicative of flow by means of cataclasis and crystal-plastic deformation.. The shocked quartz (Fig. 4) is characterized by pervasive parallel lines referred to as planar deformation features. The flow structures (Fig. 5) are anastomosing breccia dikes, 1 to 2 inches in width, consisting of large autochtonous brecciated clasts within a laminated, fine-grained,

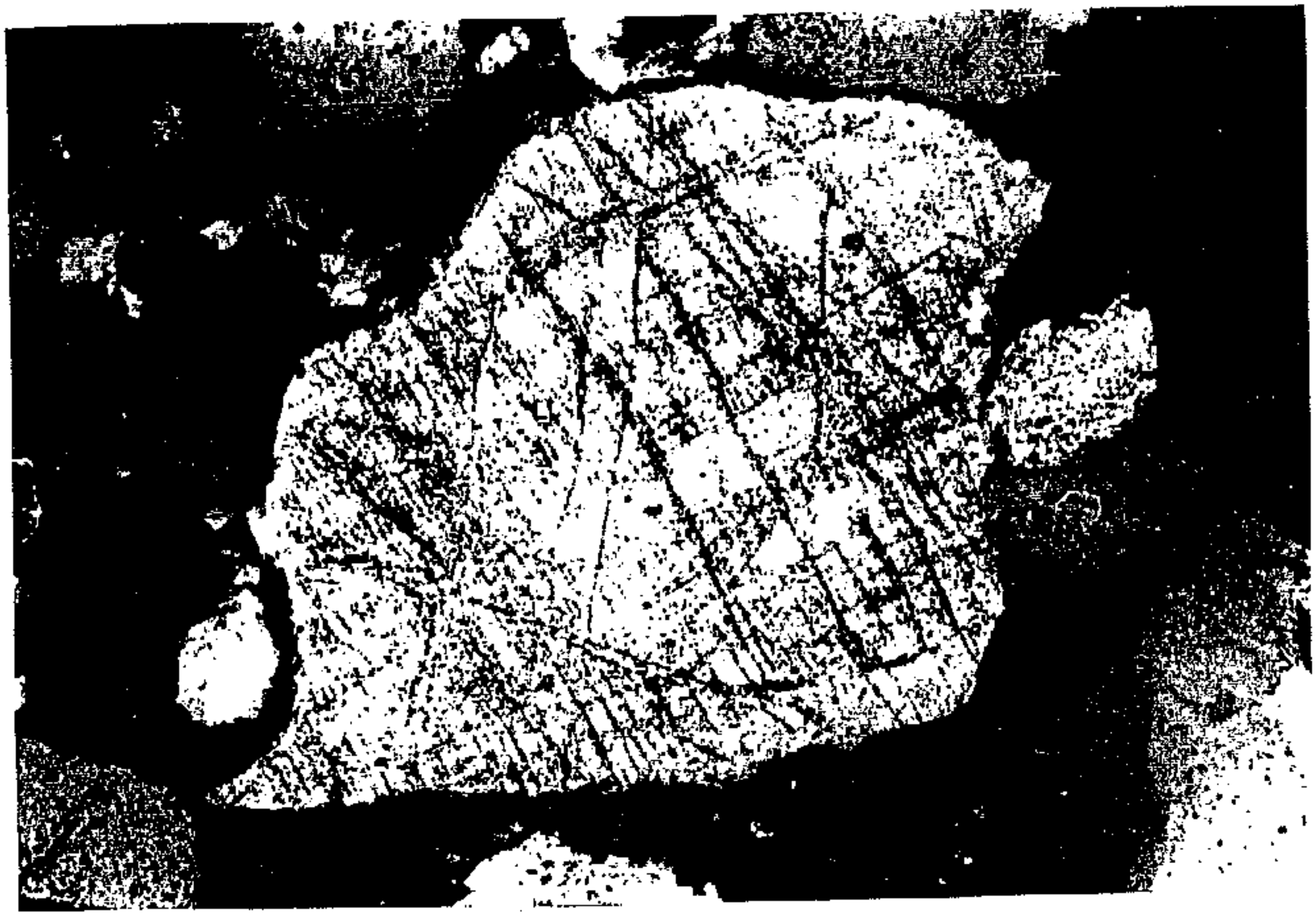


**Figure 4. Thin section from floor of crater 1 showing shocked quartz which has definitive parallel lines called planar deformation features.**

**Table 2.** **Rock samples collected from the impact craters on Sheep Mountain near Douglas, Wyoming.** Crater numbers correspond to Figure 1.

| Sample | Crater | Location | Date of Sampling |
|---|---|---|---|
| K1 | 1 | center | Jun 18, 1995 |
| K2 | 1 | west rim | Jun 18, 1995 |
| K3 | 1 | south flank | Jun 18, 1995 |
| K4 | 1 | 200 feet north of crater | Jun 18, 1995 |
| H1 | 4 | 200 feet south of crater | Dec 8, 1995 |
| H2 | 1 | south rim | Dec 8, 1995 |
| H3 | 1 | center | Dec 8, 1995 |

**Figure 5. Thin section from a crater floor showing brecciated clasts in a laminated, fine-grained cataclastic quartz matrix.**

cataclastic quartz matrix. The cataclastic quartz matrix exhibits mild but definitive preferred orientation of grains which is indicative of crystal-plastic deformation processes. These petrofabric features are indicative of extreme pressures, with the shocked quartz being associated only with the highest energy environments. Together these features can be taken as conclusive evidence for an impact, because they are isolated within an otherwise mildly deformed tectonic environment.

## DISCUSSION

The evidence assembled in this study reveals that the craters on Sheep Mountain are small meteorite impact craters. The geometric form of the features is consistent with small impact craters, especially the upturned and stratigraphically thickened rocks under the rims, and the thrusts faults which carried material outward from the centers. The two organized groups of maximum principal stresses deduced from conjugate shears reveal that two different yet superimposed stress regimes deformed the rim rocks. These are interpreted here as stresses associated with the outward directed motion of the rim rocks as the craters opened, and stresses parallel to the rings associated with rim contraction as the craters partially closed. The cataclasis and flowage petrofabrics as well as shocked quartz found in the thin sections from samples taken from the crater interiors are indicative of an impact. The presence of the shocked quartz is particularly convincing because the energies for its development far exceeds the energies associated with any other geologic processes known to have operated in the region in Phanerozoic time.

The spatial proximity and common age of the craters reveal that they represent impacts from a large body that fragmented prior to impact. Other craters may have been produced during this event but have been removed by erosion up-dip of the known examples, or remain buried by younger strata down-dip toward the northeast.

## CONCLUSION

The five craters found on Sheep Mountain south-southwest of Douglas owe their origin to impacts produced by a fragmented meteorite. The impacts date from the close of deposition of the Pennsylvanian Casper Formation.

## FUTURE WORK

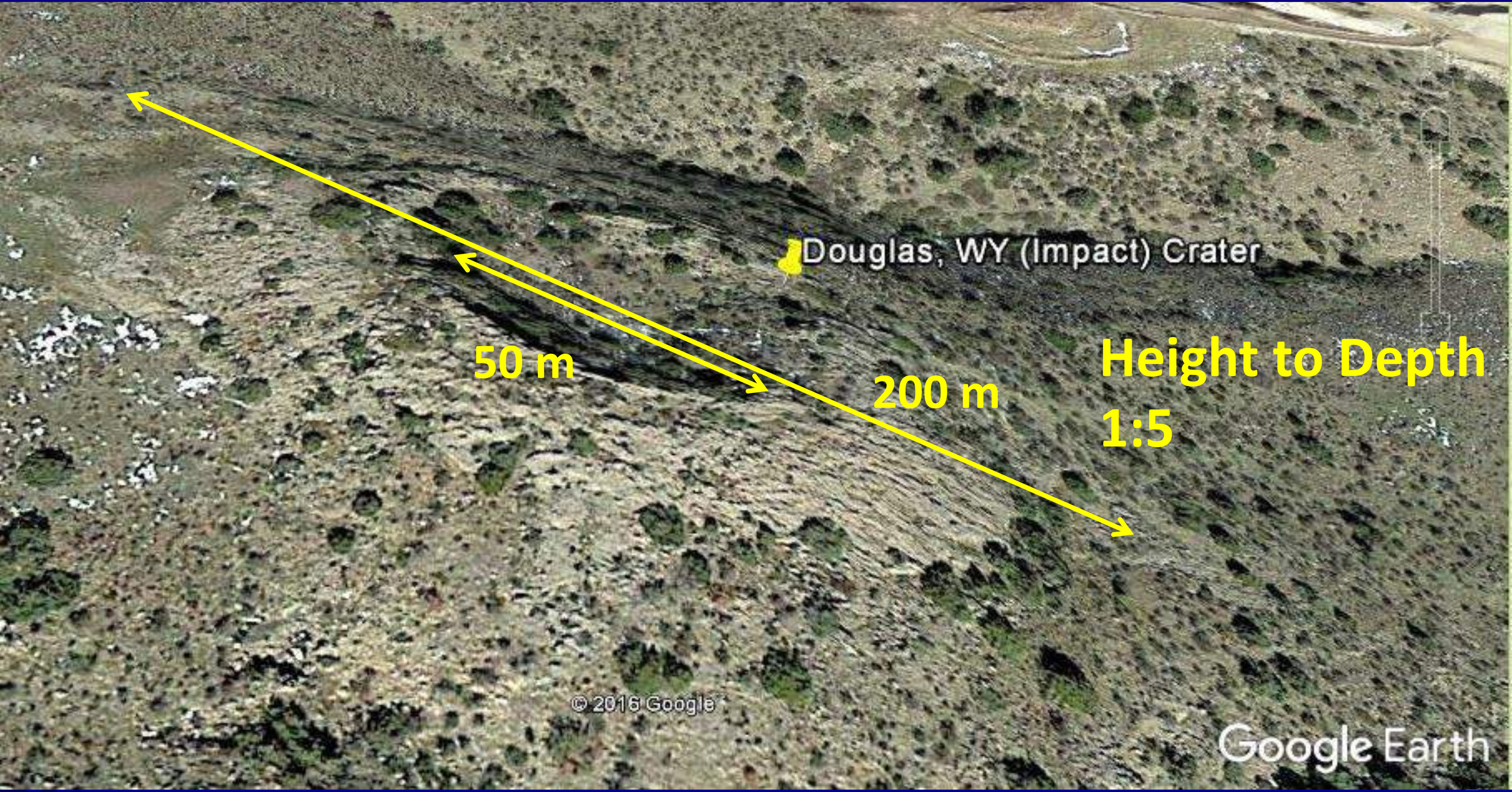
Mineralogical work is required to determine if coesite or stishovite are present in the rocks samples collected from the craters. Coesite and stishovite are high pressure phases of quartz that have proven to be reliable evidence for high speed impacts.

## ACKNOWLEDGMENTS

The project was funded by a NASA Undergraduate Seed Money Grant awarded by the Wyoming Space Grant Consortium, University of Wyoming.

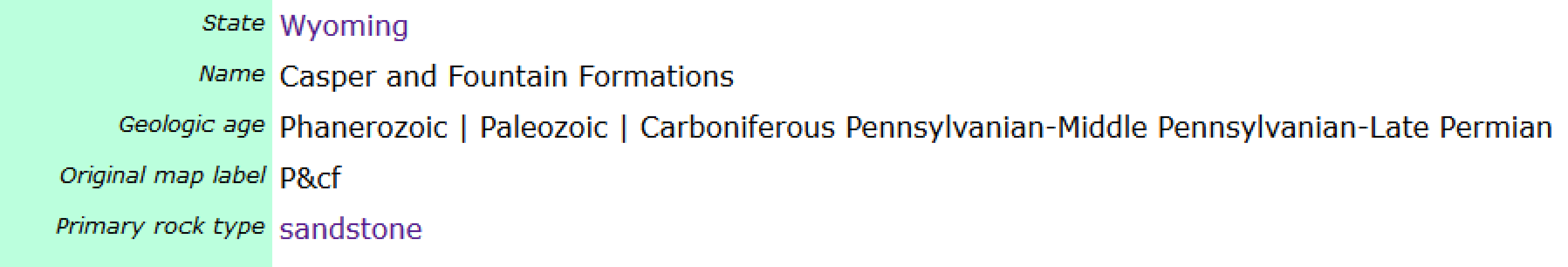
Local ranchers Bob and Georgia Garland generously provided housing for Kastning during the course of her field work. Keith Krugh of the University of Wyoming Department of Geology and Petrographic Consultants of Denver prepared the thin sections used in this analysis. Krugh provided crucial guidance in the interpretation of the thin sections.

# Douglas, WY (Impact) Crater Observations May 31, 2017



Height to Depth 1:5

# Douglas (Impact) Crater Observations May 31, 2017



| | |
|---|---|
| *State* | Wyoming |
| *Name* | Casper and Fountain Formations |
| *Geologic age* | Phanerozoic \| Paleozoic \| Carboniferous Pennsylvanian-Middle Pennsylvanian-Late Permian |
| *Original map label* | P&cf |
| *Primary rock type* | sandstone |

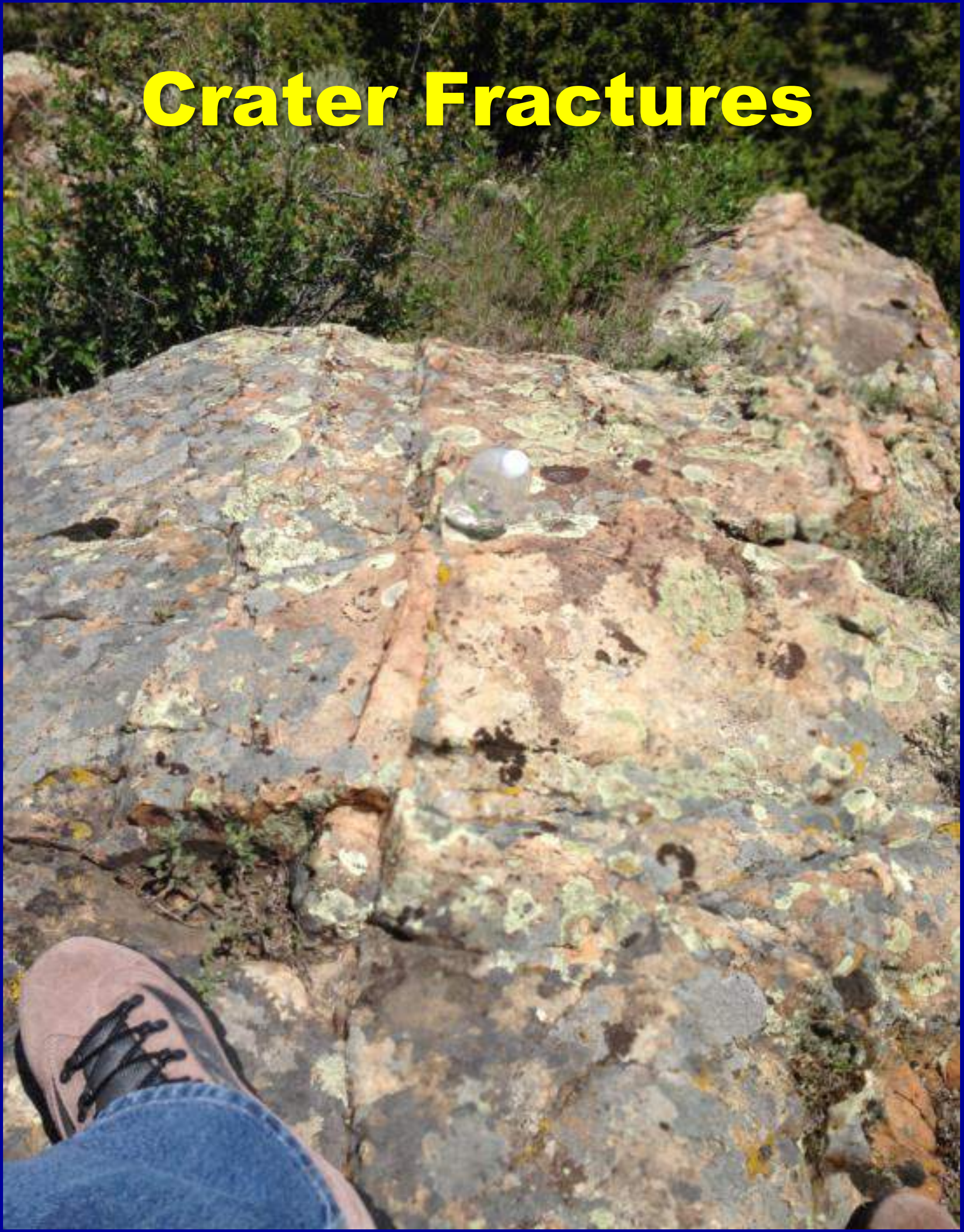
# Douglas (Impact) Crater Observations May 31, 2017
## Steep Rim Dips

# Crater In-Situ Brecciation

# Crater In-Situ Brecciation

# Crater In-Situ Brecciation

# Crater Fractures



Teapot Dome

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# Palaeobotanical evidence for a June 'impact winter' at the Cretaceous/Tertiary boundary

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**A LARGE bolide impact, such as that thought to have occurred at the Cretaceous/Tertiary (K/T) boundary, should produce large amounts of light-attenuating debris, thereby causing an 'impact winter'[1–3]. Because of thermal buffering in the oceans, evidence for a brief (1–2 months[2–4]) impact winter would be found only in terrestrial environments. Aquatic leaves in the K/T boundary section near Teapot Dome, Wyoming, preserve structural deformation that can be duplicated experimentally in extant aquatic leaves by freezing. Reproductive stages reached by the fossil aquatic plants at the time of death suggest that freezing took place in approximately early June. Both the existence of the structurally deformed plants and the high abundance of fern spores occur in a horizon containing sparse impact debris, but below the horizon containing abundant impact debris; I therefore suggest that the lower horizon represents debris and effects from a large, distant bolide impact, and the upper horizon represents a small, nearby bolide impact.**

An impact winter could produce widespread extinctions; such extinctions could indicate that a catastrophe had occurred but not the nature of the catastrophe. Tschudy[5] inferred widespread ecological disruption (but not necessarily extinction) at the K/T boundary in the western interior of North America from the fern spike, which is a sudden and marked increase in abundance of a single type of fern spore in a given K/T boundary section. Tschudy considered this to be analogous to the early successional vegetation dominated by ferns following mass-kill from large volcanic eruptions such as Krakatoa[6]. Mass-kill from volcanic eruptions, however, typically results from winds and heat generated by the eruption[7], and, except within a few hundred kilometres of the impact crater, the K/T bolide would not cause immediate mass-kill by direct transfer of thermal or kinetic energy to land organisms. Tschudy nevertheless inferred that some physical consequence of the K/T bolide impact resulted in the fern spike, because in sections analysed (mostly in the Raton Basin of New Mexico and Colorado), the fern spike occurred immediately above the impact layer[8], which contains abundant, large, shock-metamorphosed minerals and is enriched in iridium. The fern spike has also been recorded above the impact layer in eastern Montana[9] and Saskatchewan[10] but is not evident in central Alberta[11].

An apparently anomalous report[12] based on the K/T boundary section on Dogie Creek in eastern Wyoming placed the fern spike below the impact layer. At Dogie Creek, the fern spike is in the boundary claystone, an interval that had previously (especially in the Raton Basin) yielded few palynomorphs. From a Raton Basin sample of boundary claystone supplied by G. A. Izett from the Madrid East site[8], I obtained abundant, well preserved palynomorphs, 91% of which are one type of fern spore. Near Teapot Dome, 100 km west of the Dogie Creek site, the fern spike also occurs below the impact layer (Fig. 1; ref. 13). It seems, therefore, that the palynological evidence of considerable ecological disruption is present in a horizon preceding the horizon that has physical evidence of early fallout from bolide impact. But detailed palaeobotanical analysis of the Teapot Dome section (Fig. 2), which is the only western interior section that preserves identifiable plant megafossils through the boundary interval, resolves this apparent anomaly and may indicate the intensity and timing of environmental changes at the K/T boundary.

The Teapot Dome site was a lily pond, as shown by the abundance and diversity of structures of aquatic plants (Figs 2 and 3); extant relatives of some of the fossils are confined to ponds less than 2 m deep[14]. Leaves of aquatics such as the pond lily (*Paranymphaea*, allied to the extant *Nuphar* of Nymphaeaceae) and lotus (*Nelumbites*, allied to the extant *Nelumbo* of Nelumbonaceae) are typically not preserved as fossils because of very low sedimentation rates in lily ponds and the biological degradation and fragmentation of such leaves while still floating on the water surface; the Teapot Dome site, however, preserves thousands of these leaves in fine-grained sediments. The leaves are preserved, moreover, in a light-coloured clay, very unlike the carbonaceous mudstone which was the characteristic deposit in this lily pond before the boundary interval. The *Nuphar*-like rhizomes and *Nelumbo*-like growing tips (with roots) are fragmented and do not occur in their original growth positions, which could suggest high-energy transport by rapid water flow, but such transport is negated by the fine-grained sediments. The aquatic plants were suddenly killed, their below-surface roots and rhizomes were pulled off the pond bottom, and, after a period of decay, the aquatic remains were covered by an influx of fine-grained debris. The *Paranymphaea* leaves, which may have been emergent as in many extant *Nuphar*, are physiognomically like typical latest Cretaceous (but unlike early Palaeocene) leaves. I infer that the aquatic plants preserved at Teapot Dome were alive during the latest Cretaceous.

The fossils, moreover, include immature pollen of apparent Nelumbonaceae and pollen of Nymphaeaceae. Both pollen types occur in antherial masses, suggesting that they derive from flowers at or near the site of deposition. Although the pollen types are not identical to pollen of extant *Nelumbo* and *Nuphar*, the association of only two taxa of megafossils with antherial

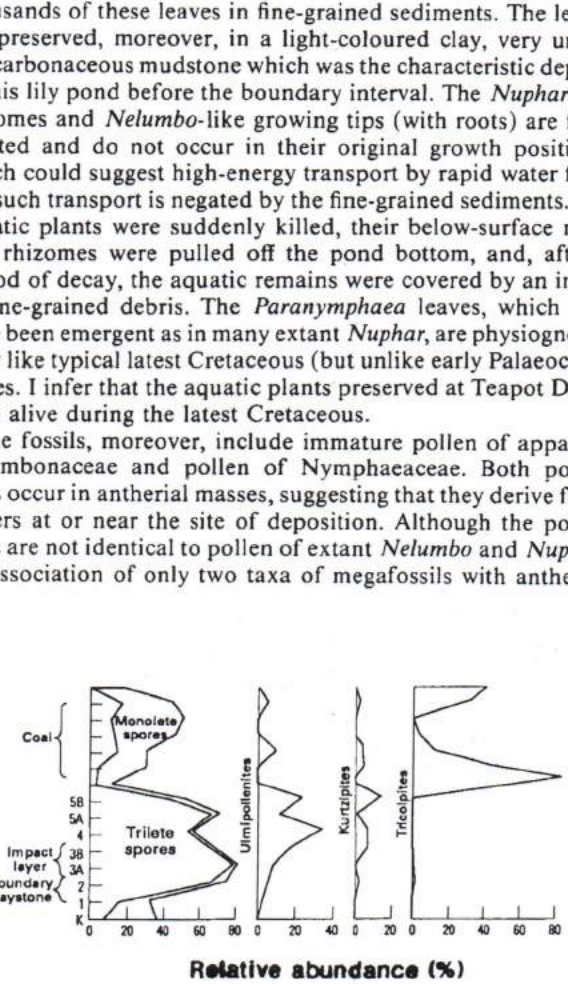

FIG. 1 Palynomorph diagram of the Teapot Dome boundary interval. The sample from bed 1 contains the typically Cretaceous *Proteacidites*. The high relative abundance of ferns (fern spike) occurs in the clasts of bed 2 below beds 3 and 4 ('impact layer'); nelumbonaceous pollen is abundant in bed 2. Relative (but not necessarily absolute) abundance of fern spores decreases as a few kinds of probable deciduous plants (*Kurtzipites, Ulmipollenites, Tricolpites*) increase. The fern spike of the clasts of bed 2 is composed mostly of a single type of fern spore, whereas the fern abundance in the upper part of the coal is composed of at least five spore types. A very few kinds of tropical ferns can grow new shoots from rhizomes and spore in 3–4 weeks (R. Foster, personal communication), and this probably resulted in the fern spike; the second fern abundance may represent sporing by plants that had grown from spores (see also ref. 7) after the impact winter ended. Ferns show no significant increase and deciduous plants continue flowering after deposition of the impact layer, suggesting that an impact winter did not result from the second impact.

farmers, but this is a social and political problem not connected to forest sustainability.

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# Concentrating mammalian urine

SIR — Alexander in News and Views[1] asserts that "The Australian hopping mouse (*Notomys*) conserves water . . . by producing more concentrated urine than any other mammal. . . To do this, it needs very long kidney tubules. . .". Actually, small rodents, including *Notomys*, concentrate urine with very short kidney tubules. In *Notomys*, the longest loops of Henle, the tubules responsible for concentrating urine, are only 5.2 mm long, and *Notomys* achieves a urine concentration of 9,370 mosmol. Horses, with loops 7 times as long, achieve maximum concentrations of only 1,900 mosmol. For all mammals, there is no trend for increased concentrating ability with increased loop of Henle length[2]. Birds decrease urine concentrating ability with increased loop length[3].

Small mammals with short loops might produce concentrated urine because of the relationship between mass-specific metabolic rate and body size[4,5]. Small mammals (and their kidneys) have more intense metabolic rates than large mammals. The mitochondrial density in the loops of Henle in small mammals (such as mice) is about twice the density of large mammals (horses), and renal mitochondria in small mammals are more densely packed with cristae than in large mammals[6]. Tubule cells of small mammals also have higher densities of basolateral membrane infoldings (insertion sites for the ion pumps that contribute to concentrating urine). Thus, small mammals may produce high urine concentrations with short loops because, compared to larger mammals, the kidneys of small mammals may have a greater capacity for the active transport underlying the concentrating mechanism.

Alexander asks why other mammals do not match the concentrating ability of desert rodents, yet few desert rodents exceed the concentrating ability of the house mouse (*Mus musculus*), not a desert specialist[7]. Why large mammals do not have greater renal mitochondrial densities may be a matter of rules relating body size to metabolic rate. Given the scant evidence relating tubule length to concentrating ability, it is difficult to understand why any mammal has any particular loop length. In sum, long loops of Henle exist more in the minds of zoologists than in the kidneys of desert rodents.

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# Plants at the K/T boundary

SIR — I cannot accept the scheme presented by Jack A. Wolfe[1] for a 'June impact' at the Cretaceous/Tertiary boundary. Not only has Wolfe extrapolated an elaborate sequence of events of global consequence from a single locality, but some of the critical evidence he cites is in my view invalid.

Wolfe reports two kinds of fossil pollen from the Teapot Dome locality that he interprets respectively as "*Nuphar*-like pollen" (Fig. 3*e*) and "*Nelumbo*-like pollen" (Fig. 3*l*). On the basis of my inspection of Wolfe's slides, which he made available to me before publication of his letter, I believe that both kinds of pollen were misidentified. Specimens of alleged pond lily (Nymphaeacea) pollen (Wolfe's Fig 3*e*) are not "*Nuphar*-like" because they lack characteristic monosulcate apertures. They are *Pandaniidites typicus* (Norton) Sweet (synonym: *P. radicus* Leffingwell), a species having a monoporate aperture; this species has probable affinity with the Pandanaceae[2]. It is common in uppermost Cretaceous (Maastrichtian) as well as lower Tertiary (Palaeocene) rocks of the region[3,4], hence its stratigraphic range exceeds that of the solely Palaeocene leaf species *Paranymphaea crassifolia*. Wolfe's argument that the co-occurrence of the leaves and pollen in his samples indicates derivation from the same plant is negated by the significant discordance in their total stratigraphical ranges.

Specimens of alleged lotus (Nelumbonaceae) pollen such as the tetrad illustrated by Wolfe (Fig. 3*l*) are not "*Nelumbo*-like" because they are tetrads (extant *Nelumbo* produces pollen as individual grains or monads of considerably larger size than the fossils) and because the fossils lack the tricolpate apertures and complexly structured walls (exines) characteristic of *Nelumbo* pollen. These fossils are *Inaperturotetradites scabratus* Tschudy, a species of uncertain botanical affinity but lacking any morphologic resemblance to pollen of *Nelumbo*. Wolfe's statement that "in extant *Nelumbo*, tetrads occur in young (immature) pollen" is irrelevant, because pollen of all species of seed plants originates as tetrads (as a consequence of meiosis during pollen genesis). Wolfe seems to have misinterpreted the caption to a drawing by Erdtman[5] illustrating the relative positions of colpate apertures on adjacent daughter cells of a tetrad during development of the pollen. Erdtman's drawing clearly illustrates the well-developed tricolpate apertures and complex exine of *Nelumbo* pollen — features lacking in the inaperturate, thin-walled fossils in the Teapot Dome samples.

More significant than these misidentifications of the fossil pollen is the observation that fossil tetrads identical to those from Teapot Dome, which Wolfe regards as immature stages from plants suddenly frozen at the Cretaceous/Tertiary boundary, are widely known from Upper Cretaceous (Campanian and Maastrichtian) rocks in Wyoming and Montana[6]. Unless countless sudden freezing events throughout Late Cretaceous time are invoked to explain other occurrences of *I. scabratus*, the Teapot Dome specimens cannot be said to represent pollen frozen during the terminal Cretaceous event. Without immature "*Nelumbo*-like" pollen to indicate unopened flowers of fossil *Nelumbites*, the hypothesis that an impact happened in June at the end of Cretaceous time has no support.

Further, my counts of fossil pollen on Wolfe's slides revealed that the tetrads in question are most abundant in bed 2 and that the misidentified specimens said to represent pond lilies are most abundant in bed 4. The law of superposition dictates that the tetrads were produced before the alleged lily pollen, the reverse of the sequence listed by Wolfe in his Table 1. Therefore, although Wolfe's analysis suggests the potential that exists for detailed analyses of the stratigraphic record at the Cretaceous/Tertiary boundary, his interpretation of the events that occured are not supported by the available data.

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SIR — Despite calling attention to the potential of microstratigraphic analysis to provide insights into geological events of extremely short duration, the letter by J. A. Wolfe[1] contains numerous palaeobotanical and stratigraphic statements to which we object.

Although fresh leaves of *Nuphar* that we froze for more than 3 weeks duplicated the pattern of fine-scale cuticular folding illustrated by Wolfe, identical patterns also appeared on *Nelumbo* and *Nuphar* leaves affixed to herbarium sheets, as well as in the epidermis of both previously frozen and unfrozen leaves allowed to dry on glass slides. The folding varied in its extent and was most commonly found near the margin, larger veins and folds, but was not seen on the cuticle of decaying *Nuphar* leaves taken directly from a water bath. After death, the mesophyll of both *Nuphar* and *Nelumbo* could be seen to undergo rapid breakdown into a gelatinous mass. From these observations we infer that such folding is the result of boundary shear stress generated by the slippage of the degrading mesophyll over the more integral epidermis, whose movement is constrained in some way, as by the leaf margin, veins or by adhesion to an interface such as that with the enclosing sediment. Thus we believe that Wolfe's implication that freezing is a unique cause of his cuticular folding is not correct.

We also take issue with some of Wolfe's palaebotanical identifications and biostratigraphical assertions: for example, leaves of the form-genus *Nelumbites* lack the hexagonal areolation possessed by all modern species of the genus *Nelumbo*; the alleged seed shown in Fig. 3*k* cannot be positively identified; and the elements in Wolfe's Fig. 3*h* cannot be reliably recognized either as "growing tips" or "Nelumbonaceae" as labelled. Further, leaves of the extinct form *Paranymphaea crassifolia* differ significantly from those of *Nuphar* in secondary vein spacing and areolation. It thus seems rash to ally *Paranymphaea* with *Nuphar* and to attribute the climatic tolerance and even time of blooming and seed-set of *Nuphar* to the fossil. We also question Wolfe's ability to determine mean *daily* temperatures using unstated methods, especially in view of the significant objections that have been raised to his leaf physiognomic methods for determining mean *annual* temperatures[7].

Far from being anomalous, ponded-water sediments are common[8] and the assemblage of plants that Wolfe describes is a normal part of the basal Palaeocene sequence for tens of metres or more above the Cretaceous/Tertiary boundary in this region[9,10]. Despite an extensive fossil record, *Paranymphaea crassifolia* has not yet been reliably identified anywhere in Cretaceous sediments. The assertion that the rhizomes of *Paranymphaea* and *Nelumbites* were lifted out of their growth position in the latest Cretaceous mudstone beneath Wolfe's bed 1 and redeposited in bed 5 of the sequence (Palaeocene) by freezing of the higher parts of the plants into an ice layer that was later buoyed by flood waters appears highly improbable in view of the lack of disruption of the Cretaceous mudstone or any evidence of remaining leaves or rhizomes in it. Additionally, our observations show that the leaves, petioles and rhizome tips of the modern analogues lose all fundamental strength upon being frozen or shortly after death, and that the leaves sink rapidly after death and are readily disaggregated after as little as 1–3 weeks at 20 °C in the laboratory. Thus, it is highly unlikely that the leaves would have continued floating long after thawing or could have had the coherency to collect sediment on their upper surfaces.

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WOLFE REPLIES — I proposed[1] a scheme for Cretaceous/Tertiary boundary events based on the Teapot Dome section, which represents an *in situ* lily pond and is the only known boundary section that contains determinable plant megafossils in the bolide fallout layers. All megafossil taxa, which represent pond lily (*Paranymphaea*) and lotus (*Nelumbites*), were discussed and illustrated; these megafossils were interpreted as remains of Cretaceous plants that suffered mass-kill. I reported a series of laboratory experiments on modern lotus (*Nelumbo nucifera*) leaves; these experiments, documented by photomicrographs, indicate that structural deformation like that in the fossil cuticle was produced by freezing but not by other environmental disturbances, including dessication. Further, the deformed cuticles are restricted to the fallout layers, which contain no evidence of dessication. Only two types of pollen occur in antherial masses and hence probably came from plants proximal to the depositional site; these pollen have characters that I interpret to ally them to extant relatives of the megafossil taxa.

Is *Paranymphaea crassifolia* in fact absent in the Cretaceous? If true, the *Paranymphaea* leaves I found 0–5 cm above the impact layer could not represent Cretaceous plants, and *P. crassifolia* must have originated *de novo* at the boundary, a most remarkable and improbable event.

Pollen morphology can be difficult to interpret. Nichols and I interpret the morphology of the spinose Teapot Dome pollen differently, and he asserts that this pollen cannot be nymphaeaceous. This pollen consistently has a single 'fold' and, despite my requests, Nichols was unable to find a 'pore' that was not obscured by a spine. I interpret this pollen as monosulcate and nonporate. Nichols also seemingly does not appreciate that different plant organs can evolve at different rates; the nelumbonaceous pollen, which is distinct from the Cretaceous taxon he mentions, does not have all specialized characters of extant *Nelumbo*, unlike the associated megafossil organs. He denies the significance of the occurrence of nelumbonaceous pollen as tetrads; if this is not significant, why did the typically terse Erdtman[5] mention this? Nichols' palynological arguments result in the improbable conclusion that in this lily pond neither *Paranymphaea* nor *Nelumbites* was represented by pollen.

If Hickey and McWeeney are attempting to show that my statements on cuticle are false, why did they experiment on *Nuphar* and not *Nelumbo*? *Nelumbites* constitutes about 98% of the megafossils, strongly suggesting that this plant was the source for the structurally deformed fossil cuticle. To observe the minor folds, I had to prepare the leaves chemically, whereas Hickey and McWeeney state that such folds ". . . appeared on *Nelumbo* and *Nuphar* leaves affixed to herbarium sheets . . .". Hickey and McWeeney's folds varied in distribution, whereas my freezing folds are ubiquitous in modern and fossil cuticles. I question whether Hickey and McWeeney are reporting the same kind of structural deformation. I also question the observations on the supposed lack of strength of aquatic organs following freezing: in my experiments, thawed *Nelumbo* leaves underwent some degradation but remained intact and floating for at least 4 months.

Determination of events at the Cretaceous/Tertiary boundary is important, and I thus allowed Nichols to examine my preparations before publication. Similarly, had they asked, Hickey and McWeeney could have examined the megafossils. Why do they now contradict my megafossil determinations without having examined the specimens?

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# The K-T boundary in terrestrial rocks:

## Context for the locality at Sussex, Wyoming

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ABSTRACT

The Cretaceous-Tertiary (K-T) boundary is present at a locality near the town of Sussex, Wyoming, in the southwestern Powder River Basin. This locality is the focus of a field trip that is part of the Tate Geological Museum's Annual Conference in 2005. The K-T boundary is identified in the field at this locality by the presence of a 1-cm-thick claystone layer beneath a coal bed. Observable only with the aid of a microscope or more elaborate instruments, the K-T boundary claystone contains both an anomalous concentration of the metallic element iridium and sand-size grains of quartz that have multiple sets of shock-induced microfractures. The iridium anomaly and shocked quartz are evidence of the impact of an extraterrestrial body on the Earth at the end of Cretaceous time, the Chicxulub impact on the Yucatan Peninsula, Mexico. The mudstone below and the coal and overlying mudstone above the boundary claystone contain fossil pollen grains and spores whose presence, absence, or relative abundance are indicators of a major extinction of plants interpreted to have been caused by the impact. This plant extinction is an aspect of the terminal Cretaceous extinction event, which most people also associate with the disappearance of dinosaurs.

The Sussex locality is one of about 50 K-T boundary localities known in terrestrial rocks from New Mexico to northern Canada, all of which are characterized by iridium anomalies and plant-microfossil evidence of extinction. A brief survey of some other localities places the one at Sussex in context and reveals some important generalities about the extinction event and the subsequent recovery of the terrestrial flora. For example, at most localities a palynofloral extinction of as much as 35 percent of Cretaceous species is documented at the K-T boundary, and a fern-spore abundance "spike" is present in the rocks just above the boundary layer. The fern-spore spike is the record of pioneer plant communities colonizing a devastated landscape.

Nichols, D. J. 2005. The K-T boundary at Sussex, Wyoming - evidence for a major extinction event revisited. Tate 2005, 11th Annual Symposium in Paleontology and Geology. p. 40-60

# The K-T boundary at Sussex, Wyoming — evidence for a Major Extinction Event Revisited

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## ABSTRACT

The extinctions of life at the end of the Mesozoic Era remain a subject of interest and controversy. The impact theory relates the disappearance of the dinosaurs, many land plants, and a host of marine organisms to an extraterrestrial body striking the Earth about 65 million years ago and causing an ecologic catastrophe that marked the close of the Cretaceous Period and the beginning of the Tertiary Period. The rocks near Sussex, Wyoming, hold clues to this event and its consequences. Evidence of environmental disruption and extinction comes from plant fossils, primarily microscopic fossil pollen grains and spores. Evidence of impact includes (1) an anomalous concentration of a rare metal (iridium) that is common in meteorites and (2) sand grains that were fractured by a massive shock. These features are found within or are closely associated with a thin layer of claystone that can be examined in an outcrop near Sussex. The Sussex locality is one of about 50 Cretaceous-Tertiary boundary localities now known from New Mexico to northern Canada, all of which are characterized by iridium anomalies and plant-microfossil evidence of extinction. A brief survey of some of the other localities places Sussex in context and reveals some important generalities about the extinction event.

## INTRODUCTION

This paper describes a locality near the town of Sussex, Wyoming, at which the Cretaceous-Tertiary (K-T) boundary has been well studied. The K-T boundary reflects the instant in time that marks the end of the Mesozoic Era. The Sussex locality was the focus of a Wyoming Geological Association field trip in 1994 (Nichols and Brown, 1994) and is to be revisited in 2005 as part of the 11th Annual Symposium in Paleontology and Geology at the Tate Geological Museum, Casper, Wyoming.

At the Sussex locality a unique sedimentary deposit marks the K-T boundary. It is a thin layer of claystone that has some remarkable geochemical and mineralogical properties. It is at the top of a thick succession of rocks dating from the Cretaceous, the last of the three periods of the Mesozoic Era, and just below a thick succession of rocks dating from the Tertiary Period of the Cenozoic Era. The Cretaceous rocks represented by the Lance Formation contain dinosaur bones; the Tertiary rocks represented by the Tullock Member of the Fort Union Formation do not. Both rock intervals contain fossils of plants that lived during part or all of latest Cretaceous and earliest Tertiary time. The plant fossils include enormous numbers of microscopic pollen grains and spores, which provide important information about the environment during those times. Fossil pollen and spores also provide valuable evidence about what happened at the close of the Mesozoic Era, about the extinction event that took place when the K-T boundary layer was deposited, and about both extinction and survival of life during those times.

This paper briefly reviews the leading explanation for the cause of extinctions at the end of the Mesozoic Era—the impact theory—and some of the evidence for it, especially as it relates to the Sussex locality. It then summarizes the geology of the locality and presents the evidence of the K-T boundary event found there. Because interest in the dominant animals of the Mesozoic Era—the dinosaurs—remains high among many amateur paleontologists and the general public, the implication especially for the extinction of the dinosaurs is considered. The following section presents some basic concepts and other information that may be useful for readers not already familiar with the background on the impact theory, the K-T boundary, and dinosaur extinction.

## BACKGROUND

### THE IMPACT THEORY

About 25 years ago, a theory was proposed that appears to provide the answer to the question of what happened at the end of the Mesozoic Era when as much as 70 percent of species suddenly became extinct. It involves an unusual event in geologic history, an event for which there is now considerable physical evidence. The theory is that about 65 million years ago, a large body from outer space hit the Earth (Alvarez et al., 1980). The occurrence of such an event would have had fatal effects on organisms living at the time, including the dinosaurs; this is the impact theory of Cretaceous extinctions. Since Alvarez and his colleagues proposed the impact theory, it has undergone extensive investigation and considerable elaboration. A fascinating account of the debate that arose among scientists after this theory was proposed is presented in the book "Night Comes to the Cretaceous" (Powell, 1998). Supporting seems overwhelming, but in this paper an attempt is made to present an objective account of the theory and some of the kinds of evidence for it that comes from the rocks near Sussex, Wyoming.

In its simplest form (Alvarez et al., 1980), the theory holds that the impacting object is thought to have been an asteroid or a comet (fig. 1). The impact raised a cloud of dust that spread through the stratosphere, darkening the skies for an interval of many weeks or months. The dust cloud blocked the sun so effectively that the Earth was significantly cooled for many months. The impact-induced darkness and cold drastically affected existing life to the extent that many species of organisms were killed off. Plants, unable to conduct photosynthesis without light, died. Herbivorous animals, unable to continue to feed on the plants of their choice, perished. Carnivorous animals starved because their food source (other animals) disappeared.

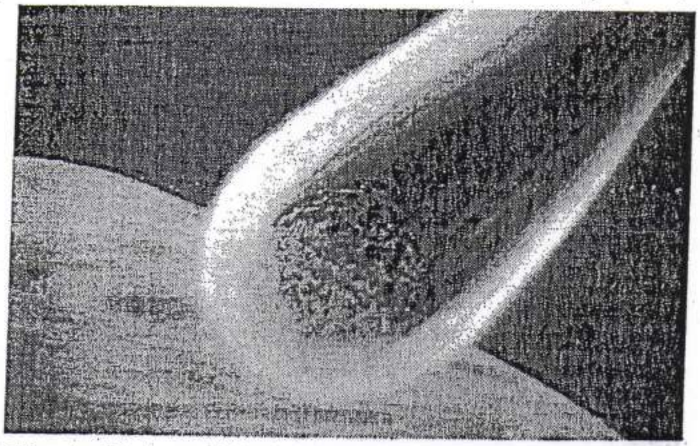

Figure 1. Extraterrestrial body (asteroid or comet) streaks toward the Earth on the last day of the Mesozoic Era (artist's conception).

Elaborations of the theory include that (1) the impact was accompanied by wildfires of global extent, which had direct effects and also added smoke to the already darkened skies; (2) the impact-induced shock to the atmosphere caused a sudden change in chemistry resulting in acid rains of monumental proportions; and (3) interactive effects of the impact and its consequences caused fluctuations in levels of oxygen and/or carbon dioxide in the atmosphere, which caused sudden, major changes in atmospheric temperature. Resulting changes in global climate have also been suggested. For example, cooling of the atmosphere may have occurred to the extent that global "impact winter" (analogous to the "nuclear winter" theorized to be a possible result of nuclear war) prevailed. Surely if conditions like these existed even temporarily, the effects on life on Earth would have been sudden and dramatic. These and other ideas are discussed in papers published in major symposium volumes—for example, Silver and Schultz (1982), Sharpton and Ward (1990), Ryder et al. (1996), and Koeberl and MacLeod (2002).

## K-T BOUNDARY

It is important to keep in mind that the K-T boundary marks an instant in time that is recognized by the extinction of certain plants and animals. In the sea, the organisms that became extinct included microscopic protozoans (foraminifera) and invertebrates such as ammonites, so their fossilized remains define the K-T boundary in marine rocks. Obviously the most famous organisms to become extinct on the land are the dinosaurs, but many kinds of terrestrial plants also became extinct at the K-T boundary, so both kinds of fossils can be used to define the K-T boundary in nonmarine rocks. Thus, rather diverse groups of fossils are used to identify the boundary in rocks deposited in the sea and on the land. Understandably, it is difficult to be sure that the same instant in time is marked by extinction of such different organisms, which lived in distinct and separate environments. How can one know that the same instant in time is being identified in both marine and nonmarine rocks?

It is the presence of iridium, a rare metallic element, that provides independent evidence that the K-T boundary identified in both marine and nonmarine rocks is the same. Based on geochemistry rather than paleontology, this element serves to correlate these rocks with a degree of accuracy unequaled in rocks of any other age. Because iridium may be found in rocks at places other than the K-T boundary, however, identification and correlation of the boundary also involves fossils. Fossils, which reveal whether the rocks are Cretaceous or Tertiary in age, are used to bracket the position of the K-T boundary with as much precision as possible. Detection of iridium then can pinpoint its exact position in the rock record, within fractions of an inch.

Thus, the K-T boundary is an instant in time at which there was a major extinction event identified by both fossils and geochemistry. In many places including the Sussex locality, the boundary can be recognized by the presence of a unique layer of claystone at the level of extinction of certain fossils and other evidence linked to the impact event.

## IRIDIUM

All discussions of the impact theory of extinction eventually involve iridium. Iridium is a rare metal related to platinum. There is iridium deep inside the Earth, associated with its iron-rich core, but it is extremely rare in rocks at the Earth's surface. However, iridium is relatively common in meteorites and asteroids. Thus, a deposit of iridium at the surface of the Earth may have come from outer space, from a meteorite that hit the Earth. Analyses to determine the presence and concentration of iridium in rock samples require the sophisticated techniques of nuclear chemistry. These techniques also enable researchers to determine whether a particular deposit of iridium came from an extraterrestrial source or, by way of volcanic activity, from the Earth's interior.

Iridium of extraterrestrial origin is present in rocks at the Earth's surface, in small but measurable concentrations, in the thin claystone layer found at the K-T boundary. Because the boundary layer is found at many places around the world (e.g., Alvarez et al., 1984), the deposit originally must have had a global distribution, and, although the amount of iridium at any one place is small, the total amount must have been very great. Such an unusual concentration of this rare metal is, therefore, considered to be anomalous. It was the discovery of the globally distributed iridium anomaly in the K-T boundary layer that led Alvarez et al. (1980) to conclude that the layer itself was deposited as dust from a large extraterrestrial body that was pulverized by impact with the Earth.

Most of the boundary layer deposits in which iridium is found originally were deposits in the deep sea (that is, they are now in marine rocks), but iridium also has been found at the K-T boundary in sediment that was deposited on the land (that is, in nonmarine rocks). The first discovery of iridium in nonmarine rocks was made in New Mexico (Orth et al., 1981). Since then, iridium anomalies have been found at the K-T boundary in nonmarine rocks at many places in western North America, including the Sussex locality in the southwestern Powder River Basin of Wyoming (fig. 2).

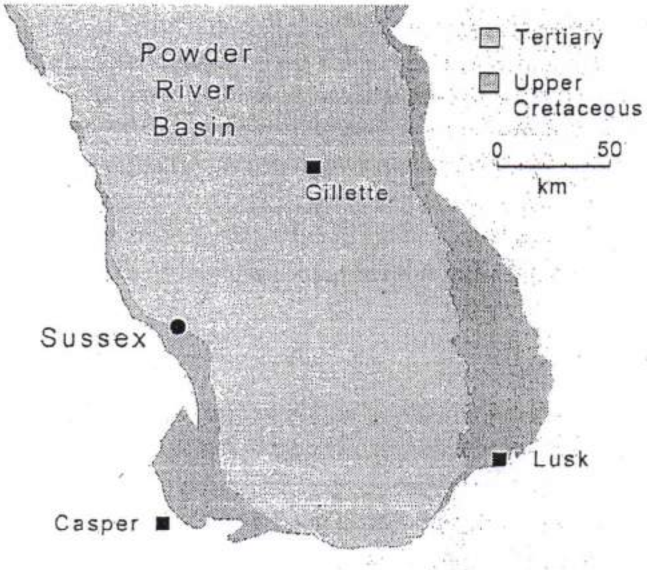

Figure 2. Map showing Wyoming part of the Powder River Basin and location of the Sussex K-T boundary locality. Upper Cretaceous rocks include Fox Hills Sandstone and Lance Formation; Tertiary rocks include Fort Union and Wasatch Formations.

## EXTINCTION OF THE DINOSAURS

Dinosaurs are without doubt the group of fossil organisms that holds the most fascination for people. These commonly bizarre and always interesting animals existed for more than 160 million years, from about 230 million years ago until about 65 million years ago, and they were the dominant animals on the land for most of that time. Although aspects of their life habits generate much curiosity, their disappearance at the end of the Mesozoic Era draws much attention as well. In fact, a great many ideas have been suggested to explain just how these great creatures, which had been so successful for so long, became extinct. A thorough review of these ideas is beyond the scope of this discussion, but a few can be mentioned. Some of them are intriguing (and conceivably could be true, at least in part) but they cannot be considered credible scientific theories because they are untestable. That is, they are not subject to serious investigation involving physical evidence. These ideas include that dinosaurs died off as a result of disease, had their eggs stolen by other creatures such as mammals, or were poisoned by newly evolved plants. These things could have happened, but there is no way to tell from the fossil record. Other hypotheses have a basis in observable, testable, geologic or paleontologic phenomena. They are more worthwhile to consider because they can be evaluated scientifically. These hypotheses include that dinosaurs died because of (1) environmental changes due to the withdrawal of seas that covered parts of the continents during Cretaceous time, (2) major changes in climate from Cretaceous to Tertiary time, or (3) adverse effects of unusual amounts of volcanic activity. Although there may be physical evidence that such geologic events did take place, there is little if any evidence linking such events to the extinction of the dinosaurs in a cause-and-effect manner. In fact, these kinds of events were so common throughout geologic history—including the Mesozoic Era—that it is difficult to understand why they might have suddenly had a drastic effect on dinosaurs at the end of Cretaceous time, when they had not for the preceding 160 million years.

Perhaps the most important aspect of dinosaur extinction is its pattern—especially whether the extinction was gradual, taking place over hundreds of thousands or millions of years, or sudden and catastrophic. Vigorous debate continues among dinosaur experts about whether, as a group, the dinosaurs disappeared suddenly or just faded away. Perhaps until that issue is settled, just what happened cannot be known. The most recent evidence available on dinosaur abundance and diversity, however, indicates that these animals were common right up until the end of the Cretaceous Period (Fastovsky and Sheehan, 2005). This is certainly true in North America, where the best records of dinosaurs are preserved (Sheehan et al., 2000; Pearson et al., 2001). Abrupt disappearance of a diverse dinosaur fauna is more compatible with the impact theory than with any other of the geologically testable hypotheses such as marine regression, climate change, or volcanism.

## PLANT FOSSILS

Although much popular interest in the K-T extinctions centers on dinosaurs, their fossil remains can seldom be used to actually identify the K-T boundary because they typically are rare and difficult to find. Plant fossils, on the other hand, especially pollen and spores, are far more numerous than dinosaur bones, and thus are more useful in identifying the K-T boundary within the stratigraphic record in most places. Furthermore, plants are key to testing the impact theory because of the direct effects a dust cloud would have upon their ability to photosynthesize. Sunlight required for photosynthesis would have been reduced or eliminated by a global dust cloud. Plants would be sensitive indicators of this impact effect; thus, their fossil record across the K-T boundary provides an important test of the theory. Studies of the plant fossil record across the K-T boundary in western North America have been conducted in two areas, one in southern Colorado and northern New Mexico (Wolfe and Upchurch, 1986, 1987) and one in western North Dakota (Johnson et al., 1989; Johnson and Hickey, 1990; Johnson, 2002; Wilf and Johnson, 2004). These studies, which are based on fossil leaves, reveal that major changes took place in plant communities at the end of Cretaceous time. The studies also show that significant permanent changes occurred in ancient forests as a result of the K-T boundary event — extinctions eliminated many of the plants that were part of the environment of the latest Cretaceous, and the forests of early Tertiary time were radically different in composition from the latest Cretaceous forests. The extensive data critically analyzed by Wilf and Johnson (2004) in western North Dakota indicate that no less than 57 percent of plant species became extinct at the K-T boundary.

No detailed studies of fossil leaves have been conducted in the vicinity of the Sussex locality, but preliminary studies indicate that strong changes in floras took place across the K-T boundary in Wyoming as well as in North Dakota. Johnson and Hickey (1990) presented such data from the Bighorn Basin of northwestern Wyoming, and Nichols et al. (1988) discussed initial results from the Powder River Basin (fig. 3). There is every reason to believe that future detailed studies in Wyoming will show comparable results to those from North Dakota because the fossil floras of both the uppermost Cretaceous and the lowermost Tertiary are closely similar in these areas.

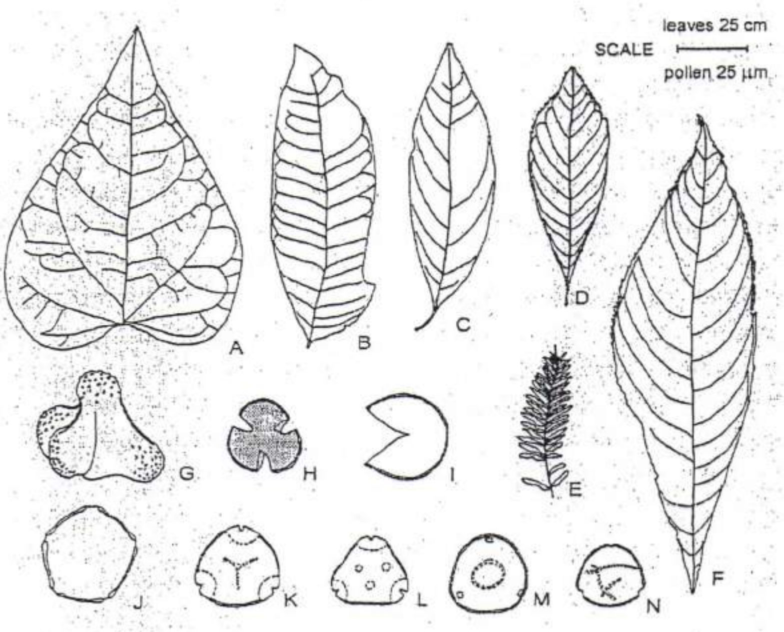

Figure 3. Illustrations of fossil leaves and pollen from the Powder River Basin (from Nichols et al., 1988). A-F, leaves from the Fort Union Formation; G-H, pollen from the Lance Formation; I-M, pollen from the Fort Union Formation; N, pollen from the Wasatch Formation.

## FOSSIL POLLEN AND SPORES

Given that plant fossils provide useful tests of the K-T boundary extinction theory, fossil pollen and spores are the most effective means for detecting changes in plants across the boundary. Despite their truly microscopic size (they cannot be seen in outcrop nor studied at all without the aid of high-power microscopes), fossil pollen and spores provide accurate and precise information on the stratigraphic position of the K-T boundary. A brief outline of the nature and significance of fossil pollen and spores is given here as an aid to understanding the fossil record at the Sussex locality; further information on these kinds of fossils and their uses in geologic studies is given by Traverse (1988). Pollen grains (which are produced by seed-bearing plants) and spores (which are produced by nonseed-bearing plants such as ferns) are among the most numerous of a large group of plant microfossils that also includes spores and cysts of certain algae and spores of fungi. Collectively these microscopic plant fossils are called palynomorphs, and their study is called palynology. Palynology is a paleontologic specialization that concerns microscopic plant fossils, a kind of "micro-paleobotany."

Pollen and spores (and other palynomorphs) are preserved as fossils because they are composed of an organic substance having amazing resistance to degradation. They were produced by the billions by plants of the past (as they are today), and they were deposited with fine sediment that formed rocks such as claystone, mudstone, shale, and coal. These tiny fossils are preserved virtually unchanged, unlike leaf fossils that may exist only as impressions, and unlike bones that have been replaced by minerals. As fossils, pollen grains and spores are like empty shells, however, and their cellular contents long since have deteriorated. They are removed from sedimentary rock for study through a complex series of laboratory procedures employing acids that can dissolve rock but will not harm the resistant organic material that forms the cell walls of pollen, spores, and other palynomorphs.

The form and structure of pollen grains and spores are extremely diverse, despite their microscopic size. More importantly, different kinds of plants produce pollen or spores of characteristic form, enabling them to be identified. Living species of a single genus of flowering plants, for example, will produce pollen grains that look like each other, but differ from those of other plant genera. This was true in the geologic past, as well. Furthermore, the different kinds of plants that have existed throughout geologic time produced pollen or spores that in most cases are of unique form and structure, such that particular kinds of fossil pollen and spores (like other kinds of fossils) are characteristic of different geologic ages. Thus, a palynologist is able in most cases to recognize the pollen of numerous different kinds of ancient plants among specimens recovered from a rock sample, and also is then able to tell the geologic age of the sample.

The Cretaceous and Tertiary rocks at the Sussex locality contain vast numbers of fossil pollen and spores. They represent many kinds of ancient plants, among which are many that are ancestors of living plants. However, especially among the Cretaceous plants, many are now extinct. In fact, they appear to have become extinct precisely at the K-T boundary. Before discussing this record of abrupt extinction, it is necessary to summarize the geology of the Sussex locality.

## THE SUSSEX LOCALITY

### Stratigraphy

In the southwestern part of the Powder River Basin, the rocks of latest Cretaceous and earliest Tertiary age are, respectively, the Lance Formation and the Fort Union Formation. In this area, the Fort Union Formation is subdivided into two units: the Tullock Member (below) and Lebo Member (above). The Tongue River Member of the Fort Union Formation, a major source of coal in the Powder River Basin, is not recognized as a separate unit in this area, but is mapped together with the Lebo Member (Love and Christiansen, 1985). Visitors to the Sussex locality will see the uppermost part of the Lance Formation and the lowermost part of the Tullock Member of the Fort Union Formation (figs. 4 and 5); the K-T boundary is at the contact between the two units.

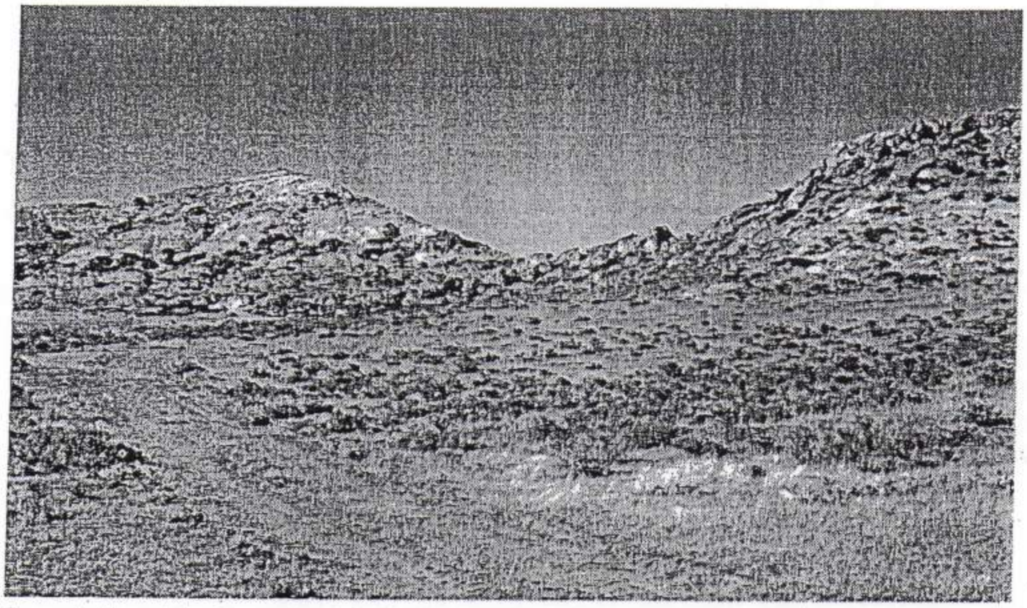

Figure 4. View of the Sussex locality. The hill at right is composed of the Lance Formation; the one at left is composed of the Tullock Member of the Fort Union Formation. The K-T boundary is near the base of the hill at left.

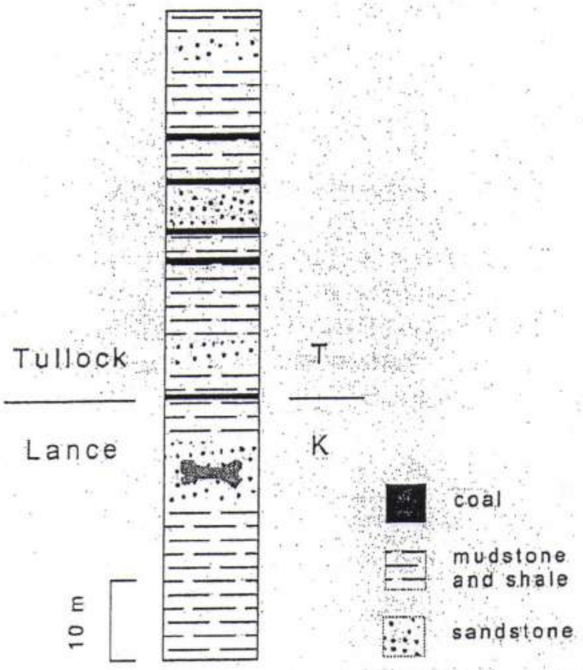

Figure 5. Diagram showing part of the stratigraphic section at the Sussex locality. The section includes the uppermost part of the Lance Formation (Cretaceous, K) and lowermost part of the Tullock Member of the Fort Union Formation (Tertiary, T). The K-T boundary is at the base of a coal bed. A fragment of dinosaur bone was found in Lance sandstone at about the position indicated by the cartoon (m, meters).

The Lance Formation is composed of nonmarine sandstone, carbonaceous shale, sandy shale, siltstone, and mudstone (Brown, 1993). Thick fluvial-channel deposits are common in the Lance, and paleocurrent directions indicate stream flow toward the east-northeast (Cherven and Jacob, 1985). The Lance ranges in thickness from about 120 meters (m) or 390 feet (ft) in the northeastern part of the Powder River Basin to about 600 m (1,970 ft) in the southwest (Lewis and Hotchkiss, 1981). Locally, bentonitic beds are common, and thin coal beds are present. The bentonitic beds characteristically weather to form a surface resembling popcorn in appearance. Typically the Lance is dull gray or tan and has a greenish cast. The formation is well known for its dinosaur remains, and in the southeastern part of the Powder River Basin it was originally known as the "Ceratops beds" (Hatcher, 1893). Dinosaur bones are less common in the Sussex area, but fragments of bone were found about 6 m (20 ft) below the K-T boundary.

The Tullock Member is composed mainly of poorly to moderately consolidated sandy siltstone, shale, minor thin coal and carbonaceous shale, and sandstone (Brown, 1993) that generally form low, brush-covered hills with few good outcrops. Typically, the Tullock is banded in appearance, gray-buff to yellow-buff in color, and generally of lighter hue than the underlying Lance Formation. Characteristically, the Tullock contains no dinosaur remains.

The Tullock Member conformably overlies the Lance Formation, and the contact between the two units is gradational. In most areas the upper part of the Lance lacks coal, but the Tullock contains discontinuous coal beds as much as 0.4 m (1.3 ft) thick. By convention and as an aid to geologic mapping, the lowest coal bed above rocks that contain dinosaur bones is used to mark the base of the Tullock Member (and the Fort Union Formation). Just beneath the basal Tullock coal bed at the Sussex locality is the K-T boundary claystone layer (fig. 6).

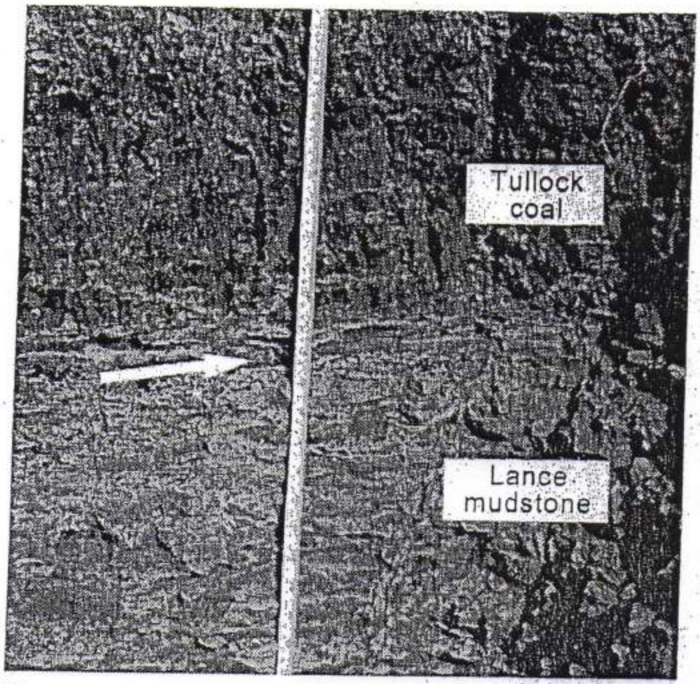

Figure 6. Mudstone of the Lance Formation (uppermost Cretaceous) overlain by coal of the Tullock Member of the Fort Union Formation (lowermost Tertiary) at the Sussex locality. K-T boundary claystone at arrow.

During the time of deposition of both the Lance Formation and the Tullock Member, the landscape in the Sussex area was much different than it is today. During the latest Cretaceous ("Lance time"), it consisted of a low-lying, well-drained fluvial plain with meandering rivers flowing eastward into the sea that had occupied the central part of the continent for millions of years but at that time was withdrawing. The climate was much warmer than it is now, and the vegetation was lush. Dinosaurs roamed the area in abundance. By the earliest Tertiary ("Tullock time"), conditions had changed markedly. Plant communities were quite different in composition, and the dinosaurs were gone. The K-T boundary layer (fig. 7) marks the end of Lance time and the beginning of Tullock time.

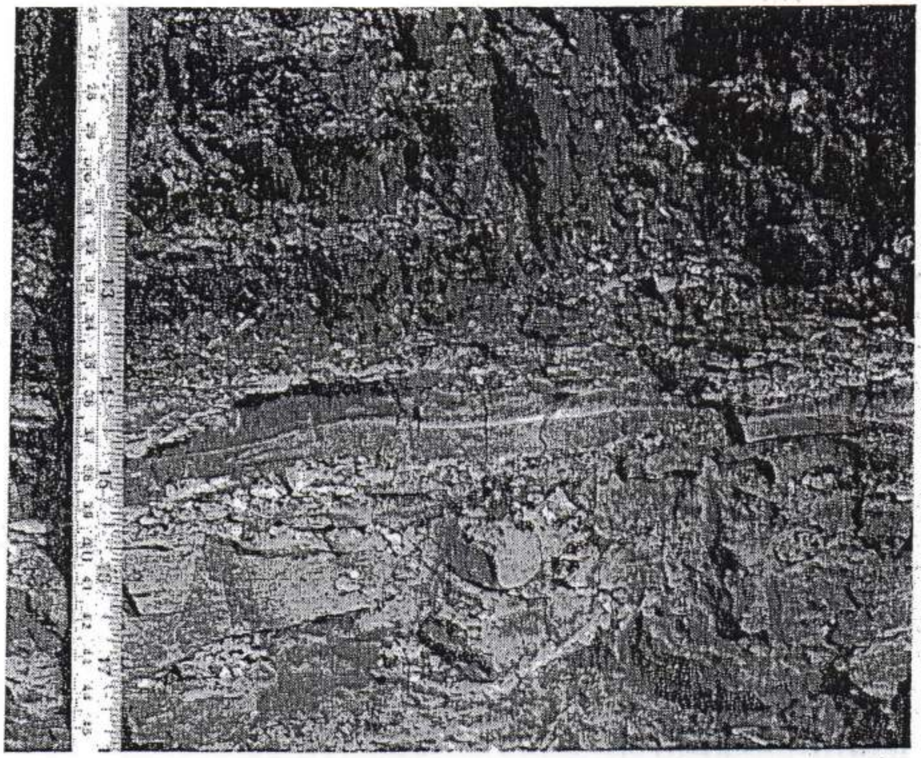

Figure 7. The K-T boundary claystone layer in outcrop at the Sussex locality. The basal coal bed of the Tullock Member is above the light-colored, kaolinitic claystone layer. Anomalously high amounts of iridium are present in the boundary layer and also in the carbonaceous layer just above it, but below the coal bed.

## BOUNDARY CLAYSTONE LAYER

The K-T boundary layer at the Sussex locality (fig. 8) is a medium- to light-gray kaolinitic claystone about 1 cm (0.4 inches) thick. Pieces of this layer can be plucked easily from outcrop. At the top is a darker, laminated claystone layer only a few millimeters thick; this uppermost layer tends to flake off when samples of the boundary claystone are collected. The uppermost layer contains sand grains (mostly of quartz). Under the microscope many of these grains show multiple sets of parallel fractures. This is the so-called "shocked quartz," which is important evidence in support of the impact theory. At Sussex the boundary claystone is separated from the overlying coal bed by a darker, carbonaceous claystone layer about 2 cm (0.8 inches) thick. Iridium can be detected in both the kaolinitic boundary layer and in the overlying carbonaceous claystone layer. In general appearance and in all-important properties, the boundary claystone layer at Sussex resembles those found at other K-T boundary localities.

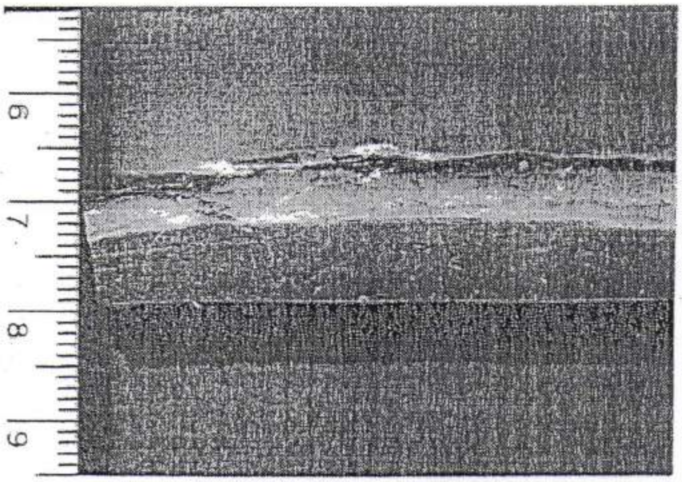

Figure 8. A sample of the K-T boundary claystone layer from the Sussex locality. Scale in centimeters.

## PALYNOLOGY

Nichols et al. (1992a) conducted detailed analyses of samples collected from a 1.2 m (4 ft) vertical interval spanning the K-T boundary at the Sussex locality. The samples were 2.5-3 cm (1-1.2 inches) in thickness and most were 2.5-5 cm (1-2 inches) apart. Studies conducted on these samples included palynological analyses (discussed here) and geochemical and mineralogical analyses (discussed later under "evidence of impact"). In their palynological analyses, Nichols et al. (1992a) recorded a total of 79 kinds (genera and species) of palynomorphs. Some genera and species were recorded only in the Lance, some only in the Tullock, and some in both units. Of the total, 72 are present in the Lance Formation and 50 are present in the Tullock Member. A few specimens are illustrated in Figure 9.

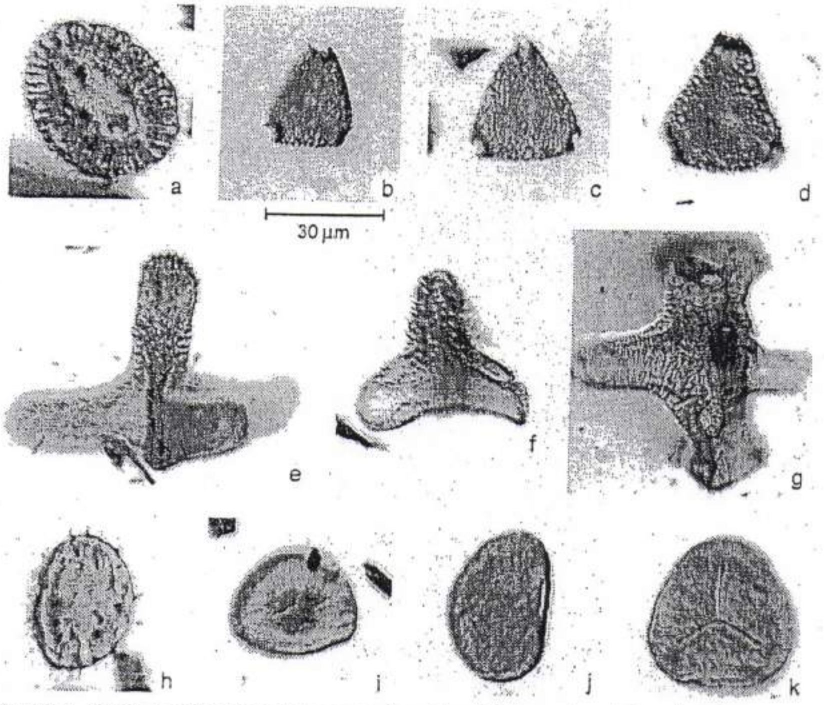

Figure 9. Some fossil pollen and spores from the K-T boundary interval at Sussex (magnified 1,000 times). a - *Wodehouseia spinata*, pollen of an extinct plant characteristic of the uppermost Cretaceous in Western North America; b-d - species of the pollen genus Tschudypollis, whose abrupt disappearance (along with other species) marks the K-T boundary; e - *Aquilapollenites collaris*, f - *Aquilapollenites quadrilobus*, g - *Aquilapollenites conatus*, all species of pollen from plants that became extinct at the K-T boundary and left no close living relatives; h - *Pandaniidites typicus*, pollen of a plant that survived the K-T boundary event (note circular aperture at 4 o'clock position on the grain, which helps identify this species); i - *Stereisporites sp.*, spore of ancient sphagnum moss from the coal bed at Sussex; j - *Laevigatosporites sp.*, spore of a fossil species of fern; k - *Cyathidites diaphana*, spore of another species of fern, from the "fern-spore spike."

The Cretaceous palynoflora consists of (1) 16 kinds of spores that were produced by ferns or related plants, including mosses; (2) seven kinds of pollen from conifers or related plants (gymnosperms); (3) 44 kinds of pollen from flowering plants (angiosperms); and (4) spores produced by five kinds of freshwater algae. Clearly the angiosperms were the most diverse major group of plants living near the end of Cretaceous time in the Sussex area. However, the palynomorphs probably represent several different plant communities. In some communities, ferns and mosses may have been more common than angiosperms. Conifers might have lived in highlands to the west, and their pollen was transported by wind or by streams to the site of deposition. The actual number of pollen grains or spores of a particular kind present in a sample gives only a rough idea of how many individual plants of a particular kind lived at or near the site of deposition. This is because different species produce widely different numbers of pollen or spores. For example, plants that pollinate by wind tend to produce vast numbers of pollen grains, whereas plants that are pollinated by insects produce far fewer.

The Tertiary palynoflora consists of (1) 16 kinds of spores of ferns and their relatives, (2) six kinds of gymnosperm pollen, (3) 24 kinds of angiosperm pollen, and (4) four kinds of algal spores. Angiosperms were still the most diverse major group of plants, although ferns and their relatives were proportionally more common in the Tertiary than in the Cretaceous. More importantly, some kinds of pollen and spores present in the Cretaceous are absent from the Tertiary; these palynological differences are very important for age determination and for indicating the kinds of plants that existed in latest Cretaceous and earliest Tertiary time.

A stratigraphic-range chart showing the occurrences of palynomorphs at the Sussex locality is useful to illustrate the change in palynofloras across the K-T boundary. Figure 10 shows sample-by-sample occurrences of the most common pollen and spores (a chart with the complete list was published by Nichols et al., 1992a). Continuations of some ranges (dashed lines in fig. 10) are based on occurrences recorded elsewhere in the Tullock Member (Nichols and Brown, 1992).

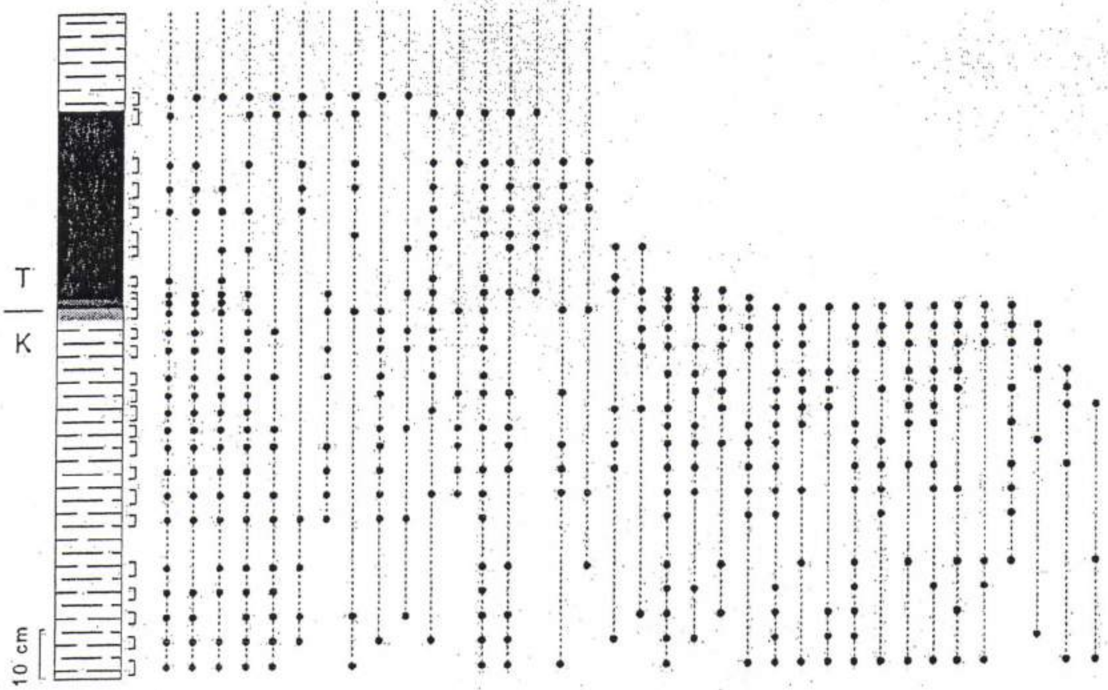

Figure 10. Stratigraphic range chart of pollen and spores at the Sussex locality. Each vertical row of dots represents a particular kind of pollen grain or spore. Each dot indicates that pollen or spores of that kind were found in a particular sample. Sample positions are indicated by brackets to right of section diagram. K-T boundary layer and overlying carbonaceous layer indicated by shaded bands; other lithologic symbols as in figure 5.

The range chart (fig. 10) reveals some interesting and significant patterns. The most obvious pattern is that many palynomorphs occur (have their stratigraphic ranges) through only the lower part of the sampled interval (the uppermost part of the Lance Formation), and that others have ranges that extend to the upper part of the sampled interval (the lowermost part of the Tullock Member). Most of the stratigraphic ranges that do not extend from the bottom to the top of the interval stop abruptly at about the same level. The line defined by the range-tops of these palynomorphs is the K-T boundary. At the Sussex locality, the K-T boundary is at the same stratigraphic level as the contact between the Lance Formation and the Tullock Member of the Fort Union Formation.

Because a coal bed marks the contact between the Lance Formation and Tullock Member, the termination of stratigraphic ranges of some palynomorphs at the K-T boundary, which indicates the extinction of the plants represented by pollen or spores, might appear to be controlled by the change in depositional environment rather than by extinction. That is, plants that inhabited the environment in which Lance Formation mud was being deposited might simply have been absent from the swamp or mire in which the basal coal bed of the Tullock Member was being formed. However, two observations show that the change in rock type does not control the occurrence of the plant microfossils.

The first observation is that pollen species absent from the coal are also absent from mudstone above the coal. Had some plants simply avoided the coal-forming environment, they would be expected to come back to the area once the environment returned to what it had been before. The second observation cannot be made at the Sussex locality alone, but only when this locality is compared with other K-T boundary localities in western North America (several of which are mentioned later). That observation is that the kinds of pollen and spores that disappear at the K-T boundary at Sussex are the same ones that disappear at K-T boundary localities throughout the entire region, from New Mexico to Canada. Thus the disappearances are not simply a local event, conceivably related to a local change in depositional environment or sedimentary facies, but a regional event, unrelated to facies change.

Another informative palynological diagram (fig. 11) shows the percentages of all kinds of spores at Sussex compared with all kinds of pollen, and the ways in which these percentages change upward through the sampled interval (which is to say, how they changed through time). The relative abundance of spores fluctuates somewhat upward through the Lance Formation and then, just above the Lance-Tullock contact, they suddenly dominate the palynomorph assemblage almost completely. At this level, 78 percent of the spores present are of a single fern species. Relative abundance of spores remains high upward into the Tullock Member, but gradually pollen returns, and although the diagram (fig. 11) does not indicate it, the dominance by a single kind of fern spores gives way to a variety of fern and moss spores.

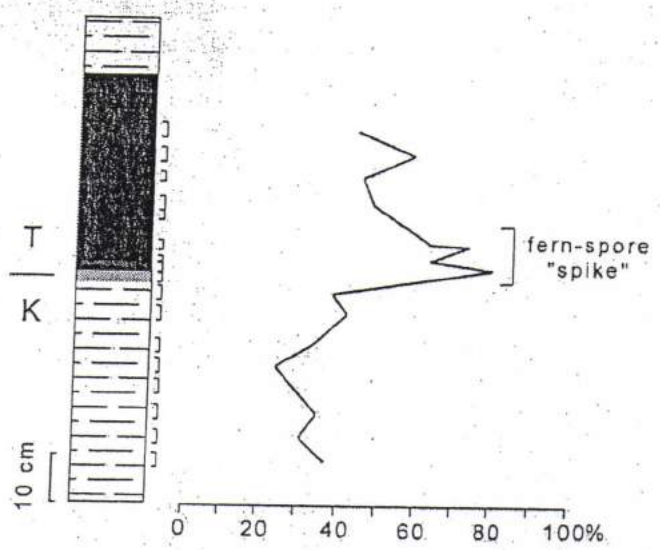

Figure 11. Diagram showing relative abundance of spores in palynmomorph assemblages in samples at the Sussex locality. The peak abundance ("fern-spore spike") is 80 percent just above the K-T boundary, and 78 percent are a single species of fern spore. Spores are also relatively abundant in overlying coal samples, but these spores include several species of ferns and mosses. Lithologic symbols as in figures 5 and 10 (cm, centimeters).

The sudden dominance of samples by fern spores nearly all of one kind is called the "fern-spore spike" and it has important implications. It implies that in the very earliest Tertiary, plant communities in the Sussex area were composed almost completely of ferns, indeed mostly of a single species of fern. As mentioned, actual numbers of pollen or spores give only a rough idea of actual numbers of plants in a community; however, where a single kind of spore is nearly the only palynomorph present in a sample, it is difficult to interpret that many plants of any other kind were nearby. Surely the fern-spore spike represents a very unusual plant community.

Because the lowermost part of the Tullock Member at the Sussex locality is a coal bed, and coal beds represent special kinds of depositional environments and plant communities (swamps or bogs), the question arises: are the fern spores simply a reflection of the depositional environment that existed in the Sussex area at the very beginning of Tertiary time? The answer is no, for two reasons.

The first reason is that fern spores just above the K-T boundary at Sussex do not simply represent a swamp or bog is that this "spike" is not unique. It is just like that found at most palynologically defined K-T boundary localities in western North America (Fleming and Nichols, 1990). It is a phenomenon of regional extent closely associated with the abrupt disappearance of Cretaceous pollen. Furthermore, it is mostly coincidental that, at the Sussex locality, the fern-spore spike is at the base of a coal bed. At other K-T boundary localities it is in rocks either below or above a coal bed, or even within a coal bed (Fleming and Nichols, 1990). Ferns were indeed present in coal-forming mires of the Tertiary, but as shown by the upper part of the coal bed at Sussex, normal communities included many species of ferns along with mosses and some flowering plants.

The second reason is that the dominance of the landscape by a single species of fern is a very unusual situation, ecologically. As pointed out by Tschudy et al. (1984), the closest analogy known in human history was observed on the remaining portions of the island of Krakatoa, Indonesia, in 1886. That island was nearly obliterated by a catastrophic volcanic explosion in 1883. All plants and animals on the surviving fragments of the island were destroyed. Three years later, plant life had returned, but it consisted almost entirely of ferns (and a few kinds of algae). Evidently ferns were able to recolonize the devastated landscape because they could quickly germinate from wind-borne spores; they were pioneer species. A few years later, seeds of flowering plants had sprouted, and ferns were reduced again to being only one of the components of diverse plant communities on the island. Tschudy et al. (1984) used the ferns of Krakatoa as a model to explain the significance of the fern-spore spike at the K-T boundary, that it represented a pioneer plant community on a landscape devastated by an extinction event.

From the palynological record at the Sussex locality, it is evident that in latest Cretaceous time, ferns were members of plant communities in the area, but just after the K-T boundary event (which involved the sudden disappearance of many kinds of flowering plants), ferns of one kind dominated an unusual community. Later in the early Tertiary, flowering plants were re-established as members of the local plant community and took their places along with ferns, eventually tending to crowd them out. However, those early Tertiary plant communities were missing a large number of flowering plant species—those that had become extinct at the boundary.

## THE K-T BOUNDARY EVENT

### DISRUPTION OF ECOSYSTEMS

Evidence that terrestrial ecosystems, which included both plants and animals, were profoundly disturbed at the K-T boundary is inescapable. Aside from the strong possibility that the dominant group of land animals, the dinosaurs, were killed off then, there are clear indications of devastation of the ecological system that had existed at the end of Cretaceous time, including (1) extinction of a large percentage of Cretaceous plants, (2) the existence for a brief time of unusual plant communities populated almost exclusively by a pioneer species of plants, and (3) a permanent change in the composition of the forests that existed from then on in North America.

At the Sussex locality, about one-third (34 percent) of the pollen and spore species present below the boundary are missing above it. Breaking down that total number by major plant groups shows that the angiosperms were most severely affected: 50 percent of the different kinds of angiosperm pollen vanished at or within centimeters of the boundary. Gymnosperms were less severely affected (25 percent of the different kinds of gymnosperm pollen disappeared), and ferns and their relatives were affected the least (13 percent of the different kinds of spores dropped out). Because different kinds of pollen and spores represent genera (or even families) of plants, not species, extinction at the species level must have been greater than these numbers indicate. As mentioned previously, data from paleobotanical studies in North Dakota indeed show a greater magnitude of extinction (57 percent or more) among fossil plant species based on leaves. Apparently the very first plants to recover from the impact event were ferns, as evidenced by the fern-spore spike just above the K-T boundary. Thus, ferns may have been just about the only plants that would have been seen during the first years of the Tertiary Period in Wyoming.

Many plants survived the extinction event, but the forests and swamps of the Tertiary were permanently missing many species that had been important members of Cretaceous plant communities. The flora of Wyoming, in fact of the entire Western Interior region of North America, had been changed forever. In a very real sense, the origin of the modern flora of the region can be traced to the K-T extinction event. The change in composition of the flora is analogous to the change from a dinosaur-dominated to a mammal-dominated fauna in the region.

### EVIDENCE OF IMPACT

Two lines of evidence at the Sussex locality indicate that the cause of the disruption of ecosystems at the K-T boundary was the impact of an extraterrestrial object. These are (1) the presence of an iridium anomaly associated with the boundary claystone layer, and (2) shocked quartz grains in the claystone. The conjunction of the evidence of impact and the extinctions argues for a cause-and-effect relationship.

At Sussex the boundary claystone layer yielded a maximum iridium anomaly of 26 parts per billion (fig. 12), the second largest anomaly ever found at the K-T boundary in nonmarine rocks. Although this may seem to be a fairly infinitesimal amount, it is actually anomalously large because it is about 1,000 times background. That is, the amount of iridium at the K-T boundary is 1,000 times as much as is present in surrounding rocks above and below the boundary. The iridium at Sussex, as everywhere at the K-T boundary, was undoubtedly derived from a huge extraterrestrial body that struck the Earth (Attrep and Orth in Nichols et al., 1992a; Orth, 1989).

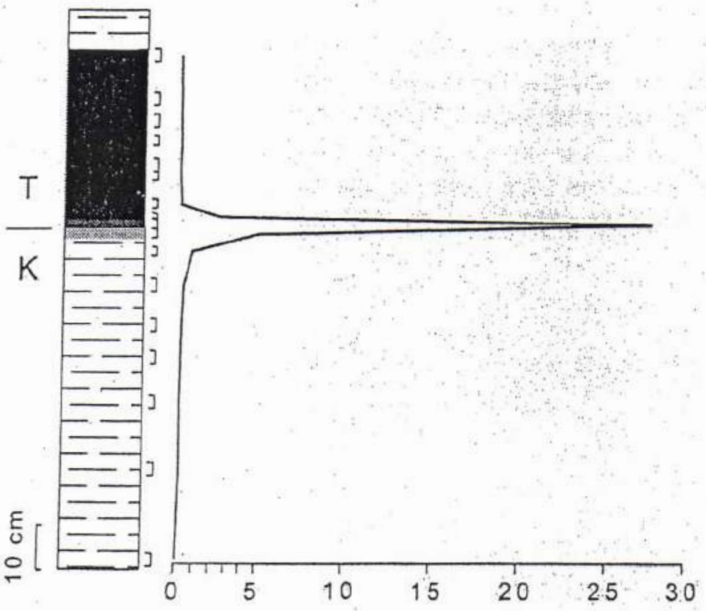

Figure 12. Diagram showing the iridium anomaly at the Sussex locality. Units are in parts per billion. Note the very low background concentration of iridium above and below the K-T boundary claystone. Lithologic symbols as in figures 4 and 9 (cm, centimeters).

Grains of shocked quartz are present in the K-T boundary claystone at Sussex (fig. 13). These mineral grains were shock-fractured by the enormous and instantaneous pressure generated during the impact. Despite some claims to the contrary, these shock features cannot be caused by volcanic eruptions, but only by high-velocity impacts (or man-made nuclear explosions). The shocked quartz grains were part of the target rock at the impact site, and they were hurled into the stratosphere, from which they settled a short time later. Shock-metamorphosed mineral grains have been found at K-T boundary localities around the world (Bohor et al., 1987a; Izett, 1990). The site of the impact crater is now known to be the Yucatán Peninsula of Mexico (Hildebrand et al., 1991). The story of how the crater, which had been sought for many years, was finally located is interestingly told in the book "T. rex and the Crater of Doom" (Alvarez, 1997).

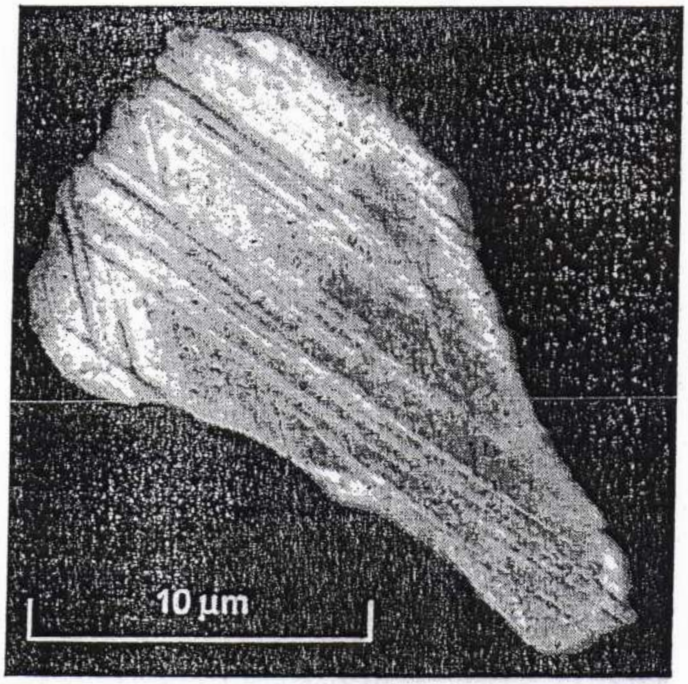

Figure 13. A grain of shocked quartz from the Sussex locality. The grain shows two intersecting sets of parallel microfractures. Length of grain 0.22 millimeters. Photo by G. A. Izett, USGS.

## OTHER K-T BOUNDARY LOCALITIES

Other K-T boundary localities in nonmarine rocks of western North America merit mention because the geologic record at those places supports the observations and interpretations made at the Sussex locality. These other localities show strong similarities with Sussex, but some also have differences that put the Sussex data into perspective. Two of these localities are in the Wyoming part of the Powder River Basin, one near Teapot Dome, about 15 km south of Sussex, and the other along Dogie Creek, near the town of Lance Creek, Wyoming, on the southeastern edge of the basin. The others are scattered through the Western Interior from New Mexico north to Canada (fig. 14).

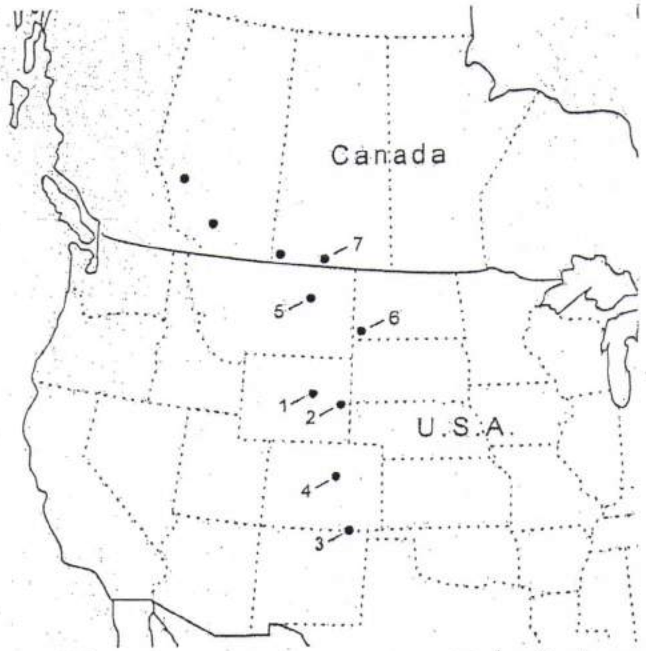

Figure 14. Generalized location map of K-T boundary localities in nonmarine rocks of western North America at which both the palynological extinction and iridium anomaly have been found. Some dots represent several individual localities. In all, about 50 such well-documented K-T boundary localities are known in nonmarine rocks.

## TEAPOT DOME

Wolfe (1991) described the Teapot Dome locality. He presented an imaginative scenario involving multiple extraterrestrial impacts, and fixed the time of year as the spring (June, to be exact). However, much of the palynological and paleobotanical evidence for Wolfe's intricate interpretation was refuted (Nichols et al., 1992b). Nonetheless, the Teapot Dome locality preserves a record of plant extinctions in conjunction with evidence of impact, including an iridium anomaly and shocked quartz. This evidence appears to be essentially the same as that from Sussex and other localities discussed here; Wolfe's overly complicated story to explain the K-T event seems unnecessary.

## DOGIE CREEK

Bohor et al. (1987b) described the Dogie Creek locality. The vicinity of Dogie Creek and Lance Creek (near Lusk, Wyoming; fig. 2) has long been known as dinosaur country (these are the previously mentioned "Ceratops beds" named for the well known Cretaceous dinosaur Triceratops). At the Dogie Creek locality there is a boundary claystone layer closely resembling that at Sussex. It is near but not at the top of the Lance Formation. As at Sussex, dinosaur bone is present below the K-T boundary at Dogie Creek; fragments there are less than 1 m (3.3 ft) below the boundary. Also at Dogie Creek, as at Sussex and Teapot Dome, the K-T boundary claystone layer contains an anomalously high concentration of iridium and also shocked quartz.

Fossil pollen and spores are present in the rocks both below and above the K-T boundary at the Dogie Creek locality. The Lance and Tullock palynofloras at this locality are closely comparable in composition and abundance to the Lance and Tullock palynofloras at Sussex; furthermore, they differ from one another in the ways described for Sussex, with about one-third of the Lance species not found in the Tullock. This observation is important, although not unexpected, because it demonstrates that the palynofloral record across the K-T boundary at Sussex is not a record of a local event. The same kinds of plants existed on both sides of the basin in latest Cretaceous time, and they suffered the same fate. A fern-spore spike is present just above the level at which characteristic Cretaceous pollen disappears at the Dogie Creek locality, but it is not at the base of a coal bed. This shows that the brief dominance of plant communities by ferns just after the extinction event was a basin-wide event, and that it was not controlled by coal deposition.

## RATON BASIN

In the Raton Basin of southeastern Colorado and northeastern New Mexico there are 15 or more separate K-T boundary localities (Pillmore et al., 1984; Pillmore and Flores, 1987; Pillmore et al., 1999). All are within the lower part of the Raton Formation, which is both Late Cretaceous and early Tertiary in age. Many of the localities are along Interstate 25 between Trinidad, Colorado, and Raton, New Mexico. At all these localities an abrupt change in palynofloras marks the position of the K-T boundary (Pillmore et al., 1984; Pillmore et al., 1999). The boundary claystone layer is present, and it contains shocked quartz and an iridium anomaly. The Raton Basin is where the first K-T boundary in nonmarine rocks was discovered, in a drill core (Orth et al., 1981). The first discovery, as all that have followed, was made on the basis of palynological and geochemical analyses made in conjunction with one another. Five localities in the Raton Basin are described in an online field guide at http://climchange.cr.usgs.gov/info/kt/.

The palynofloras of latest Cretaceous and earliest Tertiary age in the Raton Basin each differ somewhat in composition from those of corresponding age in Wyoming. This is not surprising; it shows that more than 65 million years ago the vegetation of these separate geographic areas was similar, but not exactly alike (just as today). More importantly, it shows that the K-T boundary event affected the plants of the Raton Basin in much the same way as it did in the Powder River Basin. The Raton Basin is also where the fern-spore spike was first observed and interpreted (Tschudy et al., 1984). Evidence from localities in these two basins of a landscape dominated by ferns in earliest Tertiary time further indicates that effects of the K-T boundary event were widespread.

## DENVER BASIN

Two K-T boundary localities are known in the Denver Basin of Colorado. The first was discovered about 300 m (980 ft) below the surface in a drill core (the Kiowa core described by Nichols and Fleming, 2002); the second is an outcrop locality on the eastern side of the basin (Barclay et al., 2003). The palynological extinction, fern-spores spike, and shocked quartz are present at both, and an iridium anomaly has been detected at the outcrop locality. The outcrop locality is called the West Bijou Site and it is exceptionally complete. In addition to the palynological extinction, fern-spore spike, and iridium, this locality has fossil leaves below and above the boundary and vertebrate remains are present nearby, dinosaurs below and mammals above. Furthermore, magnetostratigraphic studies in the Denver Basin (Hicks et al., 2003) place the K-T boundary interval within paleomagnetic subchron C29r, as it is in marine rocks, and radiometric dates from volcanic ash beds below the boundary are consistent with an age of 65.51 ± 0.10 million years—the most recently determined age of the K-T boundary (Hicks et al., 2002). By correlation of the West Bijou Site and the Sussex locality using the palynological extinction and the iridium anomaly, the geologic age of the K-T boundary at Sussex can also be established as 65.5 million years.

## WILLISTON BASIN

Except for the Raton Basin, the Williston Basin in southwestern North Dakota is the area in which the K-T boundary has been most extensively studied. At one locality in that area called Mud Buttes, the K-T boundary is thoroughly documented by presence of the palynological extinction, claystone layer, iridium anomaly, and shocked quartz, and there are 16 other localities that have been identified palynologically (Nichols and Johnson, 2002). In this area, data on the K-T boundary event from fossil pollen and spores is strengthened by data from fossil leaves (Johnson et al., 1989; Johnson and Hickey, 1990; Johnson, 1992; Johnson, 2002). Thorough collections of thousands of specimens of fossil leaves have been made from both the uppermost Cretaceous Hell Creek and lowermost Tertiary Fort Union Formations at numerous localities. At the Pyramid Butte locality the K-T boundary is at the top of a thick coal bed that marks the base of the Fort Union Formation. It is identified by the palynological extinction, a small iridium anomaly, and shocked quartz. An extraordinary change in fossil leaf floras is seen in collections from stratigraphically below and above the coal bed. The turnover in composition of the flora of latest Cretaceous age to that of the earliest Tertiary is remarkable. Initially the paleobotanical data indicated that 79 percent of the plant species that were living in the northern Great Plains in latest Cretaceous time were not present in the earliest Tertiary (Johnson et al., 1989), although more recently that number was readjusted to 57 percent (Wilf and Johnson, 2004).

The level of extinction of fossil leaves is much greater than that indicated by fossil pollen from the same area, which show an extinction level of about 30 percent (Nichols and Johnson, 2002). These differences in numbers are understandable if it is understood that fossil pollen of a particular kind usually represents one genus of plants, a genus that may have many species. Fossil leaves of a particular kind usually represent a single species of plant. Thus, a genus having many species may be represented in the fossil record by many kinds of leaves, but only one kind of pollen.

## HELL CREEK AREA

The Hell Creek area of eastern Montana, which is actually a western extension of the Williston Basin, contains many localities at which the K-T boundary has been located (Bohor et al., 1984; Smit and van der Kaars, 1984; Nichols and Fleming, 1990; Hotton, 2002). The Hell Creek area also has long been known as dinosaur country, and many skeletons have been collected from the Hell Creek Formation. The K-T boundary localities in this area have the now-familiar lines of evidence of a major event at the end of Cretaceous time: plant extinctions, as indicated by the fossil pollen record; brief dominance of plant communities by ferns, as suggested by the fern-spore spike; geochemical evidence of an extraterrestrial impact (the iridium anomaly); and mineralogical evidence of impact (shocked quartz). All of these lines of evidence are found within or just above a claystone layer about 1-2 cm (0.4-0.8 inches) thick.

As at all localities in nonmarine rocks in North America, the K-T boundary claystone in the Hell Creek area is associated with coal deposits. The reason for this association is that a quiet (low-energy) depositional environment in which fine sediment and plant debris tend to accumulate is the kind of environment in which the dust from the impact could settle and be preserved.

## CANADIAN LOCALITIES

At Morgan Creek, Saskatchewan, not far across the international border from the Hell Creek area, the palynofloras of latest Cretaceous and earliest Tertiary age are quite similar in composition to those of corresponding age from eastern Montana and western North Dakota. They differ in composition somewhat from those in Wyoming, and more strongly from those in southeastern Colorado and northeastern New Mexico. Nichols et al. (1986) described the K-T boundary at Morgan Creek; it was revisited and redescribed by Sweet and Braman (1992). All the familiar elements are present: a palynological extinction primarily involving angiosperm pollen and a fern-spore spike, which indicate profound disruption of terrestrial ecosystems, and an iridium anomaly and shocked quartz, which indicate that the disruption of ecosystems was caused by the impact of an extraterrestrial object.

Other K-T boundary localities have been found in Canada as far north as the Northwest Territories, as described by Sweet et al. (1990; 1999). Although the boundary at all these localities is marked by a palynological extinction, the abruptness of the extinction and perhaps its magnitude appears to be reduced in comparison with localities to the south. Sweet and his colleagues suggest that the K-T boundary event was superimposed on plant communities that were already in transition toward the end of Cretaceous time, being affected by changes in climate and sedimentary environment. Alternatively, the northern localities, which were farther removed from the site of impact, suffered less from its direct effects.

## IMPLICATIONS FOR DINOSAURS

The evidence for a major impact event at the K-T boundary is compelling, and the evidence of major disruption of terrestrial ecosystems at the time of the impact is unambiguous from the palynological record. It is difficult if not implausible to imagine how dinosaurs would not also have been drastically affected by such an event. Furthermore, assertions that the dinosaurs as a group were fading away toward the end of Cretaceous time are not supported by the most recent studies of their diversity and abundance in North America. Implications of the impact theory for dinosaur extinction seem clear enough, but readers are left to make their own judgment.

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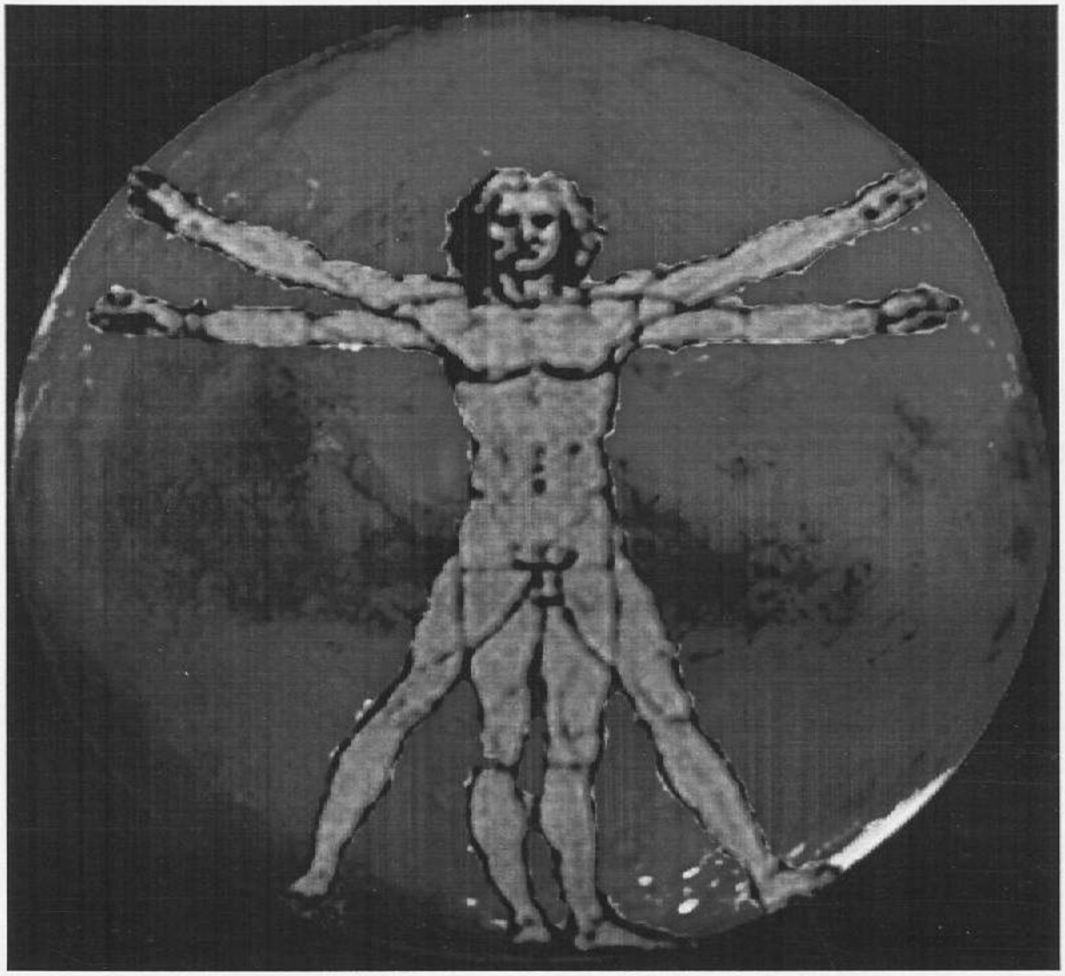
# NASA's
# Wyoming Space Grant Fellowship Program

## Graduate and Undergraduate Fellowship Reports

*1995/1996 Space Science Research*



Edited by Teresa M. Ciardi & Paul E. Johnson

# Forward

The Wyoming Space Grant Consortium sponsors research in the planetary and space sciences, primarily via Graduate and Undergraduate Fellowships. Fellowships are awarded annually for new, "cutting-edge" research. The student fellowship programs continue to enhance interdisciplinary research and the research infrastructure at the University of Wyoming. Fellowships are awarded according to specified criteria. Graduate Fellowship proposals must meet or exceed the following criteria:

- Quality of the research proposal, and the likelihood that publications and/or proposals to NASA will result
- Academic and research track records of the students and advisors
- Relevance of proposal to NASA (in a broad sense)
- Availability of matching funds
- Availability of necessary data and equipment

We fund proposals of the highest caliber only. Research projects are expected to have a high probability for being funded directly by a federal agency once preliminary research has been accomplished. The Undergraduate Fellowship goals differ from those of the Graduate Fellowship program in that the primary goal is to provide undergraduate students with exceptional research experience. Undergraduate Fellowship proposals must meet or exceed the following criteria:

- Technical and scientific merit of the research
- Academic and research track records of the principal investigators/mentors
- Pedagogical value of the project to the Undergraduate Fellow
  - a) Will the project provide the student with a valuable research experience?
  - b) Will the project result in a publication for the student?
- The inclusion of clear goals and milestones for the student
- Relevance of the research project to NASA (in a broad sense)
- Availability of matching funds

Students who receive a Graduate or Undergraduate Fellowship typically have a GPA of 3.5 or higher. In both cases, women and minorities are encouraged to apply.

All student fellows have one or more mentors who provide guidance; however, it is the student who is primarily responsible for the research. The student researchers are expected to present a talk to their peers upon the completion of their research tenure, and most submit papers and proposals as a result of the research funded by the Wyoming Space Grant Consortium. Furthermore, Undergraduate Fellows often decide to enter graduate school as a result of their research experience.

This collection contains ___ final reports from Graduate and Undergraduate Fellowships awarded in 1995. Graduate Fellowships are typically for the academic year; Undergraduate Fellowships are utilized primarily in the Summer but may continue during the academic year. Final reports are generally written by the primary researcher, the student. We have presented the reports in alphabetical order with Graduate Fellowship reports preceding Undergraduate Fellowship reports.

Please contact Teresa Ciardi, Project Coordinator, at (307) 766-2862 or via e-mail (teresa@uwyo.edu) for further information on Wyoming Space Grant Student Fellowships and other program activities. The Wyoming Space Grant mailing address is: **Wyoming Space Grant Consortium, Physics and Astronomy Department, University of Wyoming, P.O. Box 3905, Laramie, Wyoming, 82071**.

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## Graduate Fellowship Reports

## Undergraduate Fellowship Reports

PETER W. HUNTOON
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June 17, 2017

The cluster of "craters" described here that lie south of Douglas, Wyoming, are peculiar and curious features. I remain skeptical that they in fact are of impact origin. The shocked sample in the thin section illustrated on Figure 4 is suggestive but not definitive, so a repeat sample should be analyzed by an expert to confirm that it indeed represents true shocked quartz of impact origin. The sample shown on Figure 4 did not survive my retirement and move from the University of Wyoming, so is unavailable.

Peter Huntoon

# Cluster of Five Small Pennsylvanian Meteorite Impact Craters on Sheep Mountain near Douglas, Wyoming

Heather Kastning
Peter W. Huntoon
Department of Geology and Geophysics
University of Wyoming
Laramie, WY 82071

## ABSTRACT

A cluster of five small meteorite craters has been identified on the north flank of Sheep Mountain, 8 miles south-southwest of Douglas, Wyoming. The impacts occurred approximately 300 million years ago because they deformed the strata that now comprise the upper quartzite member in the Pennsylvanian Casper Formation and were subsequently buried. The cluster of craters represents an object that broke into at least five pieces before impact. The preserved deformed zone around the largest crater measures about 370 feet in diameter. The primary evidence supporting an impact origin for the craters includes: (1) a crater geometry characteristic of small impacts and (2) shocked quartz. No fragments of the meteorite are preserved at the site and no shatter cones have been found in the deformed rocks.

## INTRODUCTION

Spelman (1959) observed several circular depressions, including Crater 1 treated here, in the upper quartzite member of the Casper Formation on the northeastern flank of Sheep Mountain anticline. He did not interpret their origins. George (1994, personal communication) independently discovered Crater 1, concluded that it appeared to be of impact origin, and reported its existence to Peter Huntoon at the University of Wyoming. We undertook an inventory of the circular features on Sheep Mountain and concluded that five were of probable impact origin.

## PROCEDURES

An inventory was made to locate the circular features on Sheep Mountain with the objective to differentiate those of probable impact origin from breccia pipes, paleo-sinkholes, landslides and eroded depressions. If the feature had upturned rims, ring faults and/or highly deformed core rocks, it was considered to be a potential impact. It was then located on low-altitude aerial photography and its position transferred to a topographic map. The suspected craters were numbered from largest to smallest.

Next, detailed site characterization of the suspected craters was undertaken. The planimetric and cross-sectional forms of the craters were delineated, and the diameters measured. The radial position of all ring structures were measured, and the rings were classified as to whether they were interior-facing crater walls, the most elevated crest of the crater rims or low-angle thrusts. The cross-sectional form of the craters were documented including the vertical shapes of the faults, stratigraphic thickening within the displaced rock comprising the crater rims, and stratigraphic dips in the profile.

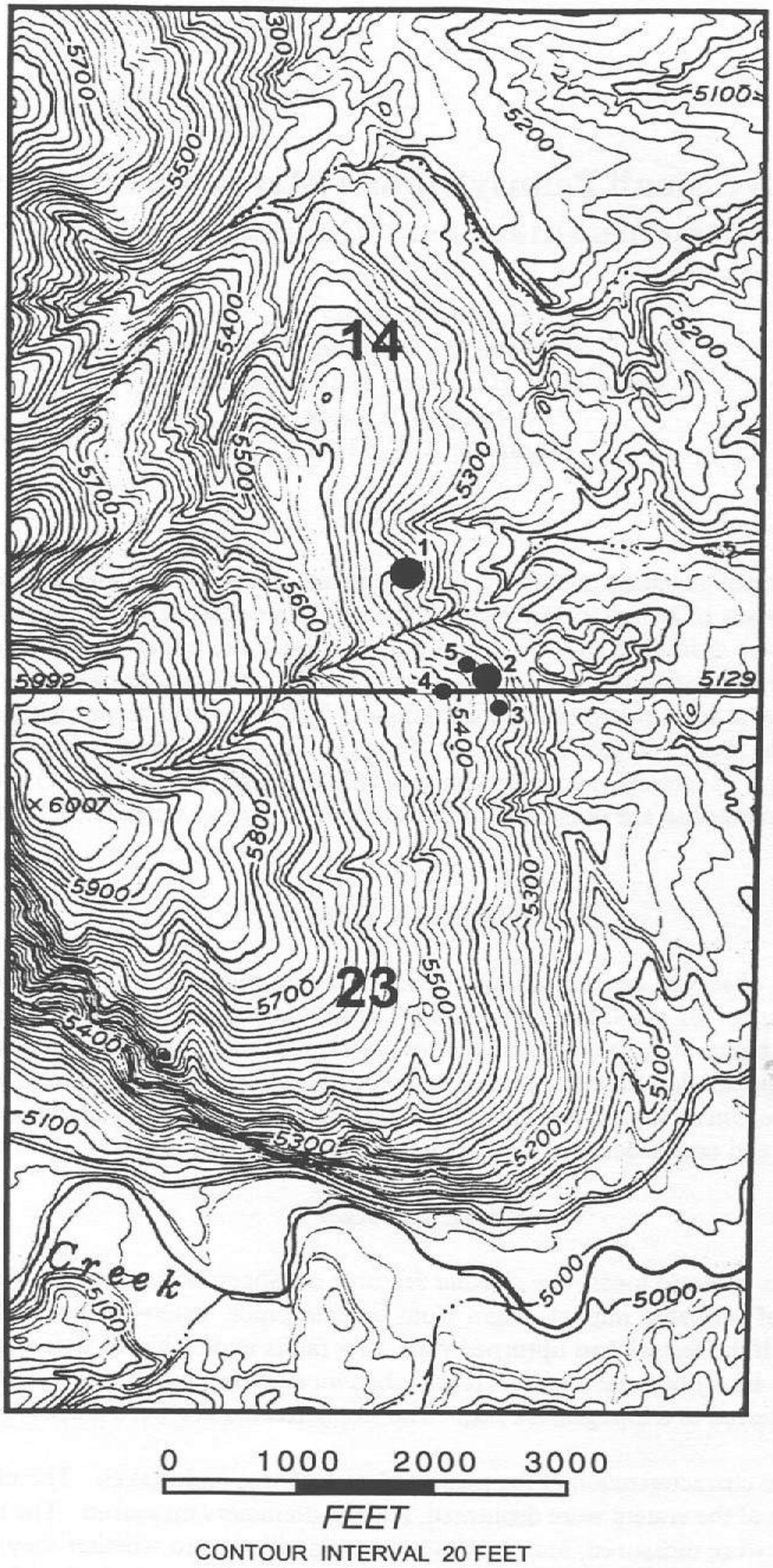

**Figure 1.** **Location and numbers of the small impact craters on Sheep Mountain, 8 miles south-southwest of Douglas, Wyoming. The area shown encompasses sections 14 and 23 of T31N, R72W. Topographic base from Chalk Buttes, Wyoming, 7.5 minute topographic quadrangle.**

**Table 1. Crater size and radii to key structural elements in feet for the impact craters on Sheep Mountain near Douglas, Wyoming.** Crater numbers correspond to Figure 1.

| Crater | Radius | Radius to Rim | Radius to First Ring Fault | Radius to Second Ring Fault |
|---|---|---|---|---|
| 1 | 185 | 100 | 115 | 185 |
| 2 | 145 | 58 | 67 | 145 |
| 3 | 90 | 69 | 90 | |
| 4 | 80 | 52 | 80 | |
| 5 | 49 | 43 | 49 | |

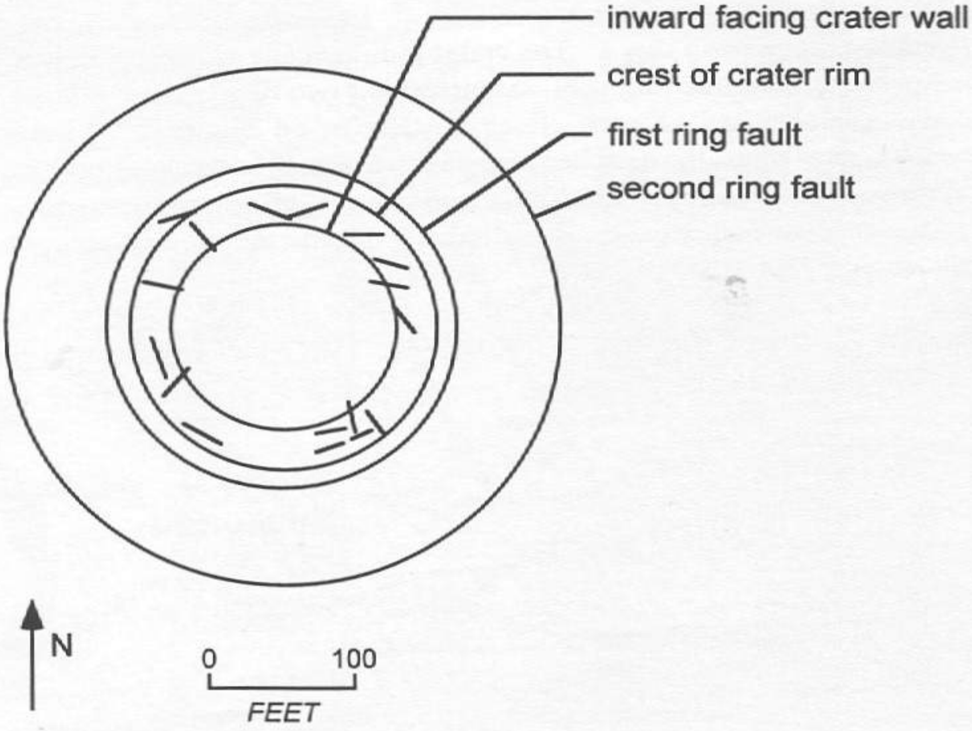

**Figure 2. Idealized sketch map of Crater 1 showing the location of various ring features, and the locations and orientations of the maximum principal stresses (short line segments) deduced from conjugate shears.**

Conjugate shear fractures in the rocks comprising the upturned rims were mapped. This was undertaken in order to determine the maximum principal stress orientations so that strain patterns could be deduced.

Rock samples were collected in order to perform thin section analyses. The locations of the samples were recorded. Rock samples were collected from various radial positions within the deformed zones comprising the craters as well as from undeformed country rock in nearby outcrops. The purpose of collecting these samples was to examine them for cataclasis, flowage and the possible presence of shocked quartz using standard laboratory thin section analytical techniques.

Photographs were taken to: (1) show the setting of the craters and (2) record visible structures such as ring faults, brecciation and flowage.

## DATA ANALYSIS

Five craters were located on the northeast dipping flank of the Sheep Mountain anticline. The impacts occur in the upper quartzite member of the Pennsylvanian Casper Formation which has been stripped of overlying sediments by erosion. The craters are deeply eroded so that no strata younger than the Casper Formation remains in them. Some of the crater rims have been breached by erosion and the floors of some of the craters have been partially dissected. Fortunately, what remains is well preserved due to the hardness of the Casper quartzite. Missing are the rocks that buried the craters, shatter cones, melt rocks and meteorite fragments.

The locations of the craters are shown on Figure 1. The radii of the craters, and position and type of the ring structures appear in Table 1. The crater radii range from 49 to 185 feet. Each crater has an obvious rim and at least one ring fault. Some exhibit two ring faults.

Cross sectional sketches of each crater are shown on Figure 2. Commonalities include stratigraphic thickening within the detached plates with the thickest sections occurring directly under the crests of the rims. Stratigraphic dips that are both inward and outward away from the crests. One or two low-angle thrust faults that crop out radially outside the rim that served to move material outward (Shoemaker, 1963).

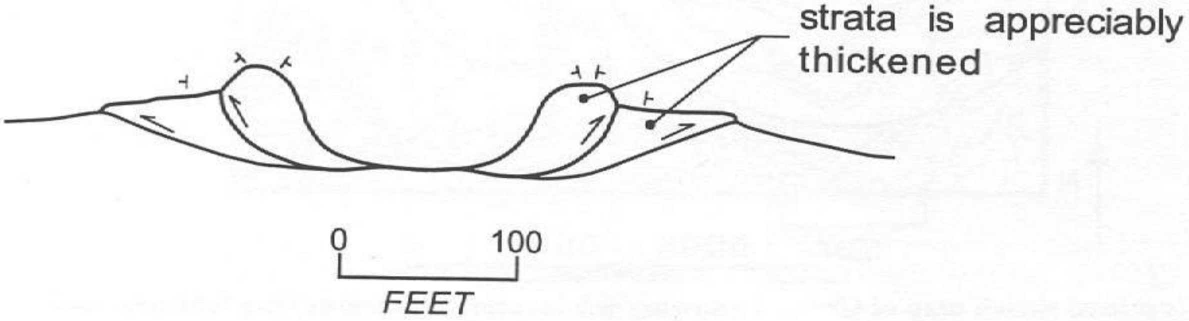

**Figure 3. Simplified structural profile through Crater 1. Dip symbols show the attitude of the strata at the surface in the displaced rings. The vertical scale is exaggerated.**

The rocks in the floors of Crater 1 are exposed and some are locally brecciated. In addition, outcrops in Crater 1 and other craters contain dikes that exhibit flow-banded, recemented rock.

A plan view of crater 1 appears on Figure 3 which shows the locations and orientations of the maximum principal stresses as deduced from conjugate shears fractures. The maximum principal stress tensors were interpreted from the conjugate shears by passing the tensor through the acute angle. Two organized populations of maximum principal stresses are present along with others with random orientations. The organized populations are oriented radial and concentric to the crater. We interpret the radially-oriented tensors as originating during the excavation flow stage (Melosh, 1989) as the crater opened. Those parallel to the circumference probably developed during the gravity modification stage (Melosh, 1989) as the crater collapsed and the mobile plates above the ring thrust faults moved inward.

The thin sections made from the samples listed in Table 2 were particularly definitive. Samples from the crater interiors revealed pervasive cataclasis of quartz grains, the presence of shocked quartz, and convoluted laminations indicative of flow by means of cataclasis and crystal-plastic deformation.. The shocked quartz (Fig. 4) is characterized by pervasive parallel lines referred to as planar deformation features. The flow structures (Fig. 5) are anastomosing breccia dikes, 1 to 2 inches in width, consisting of large autochtonous brecciated clasts within a laminated, fine-grained,

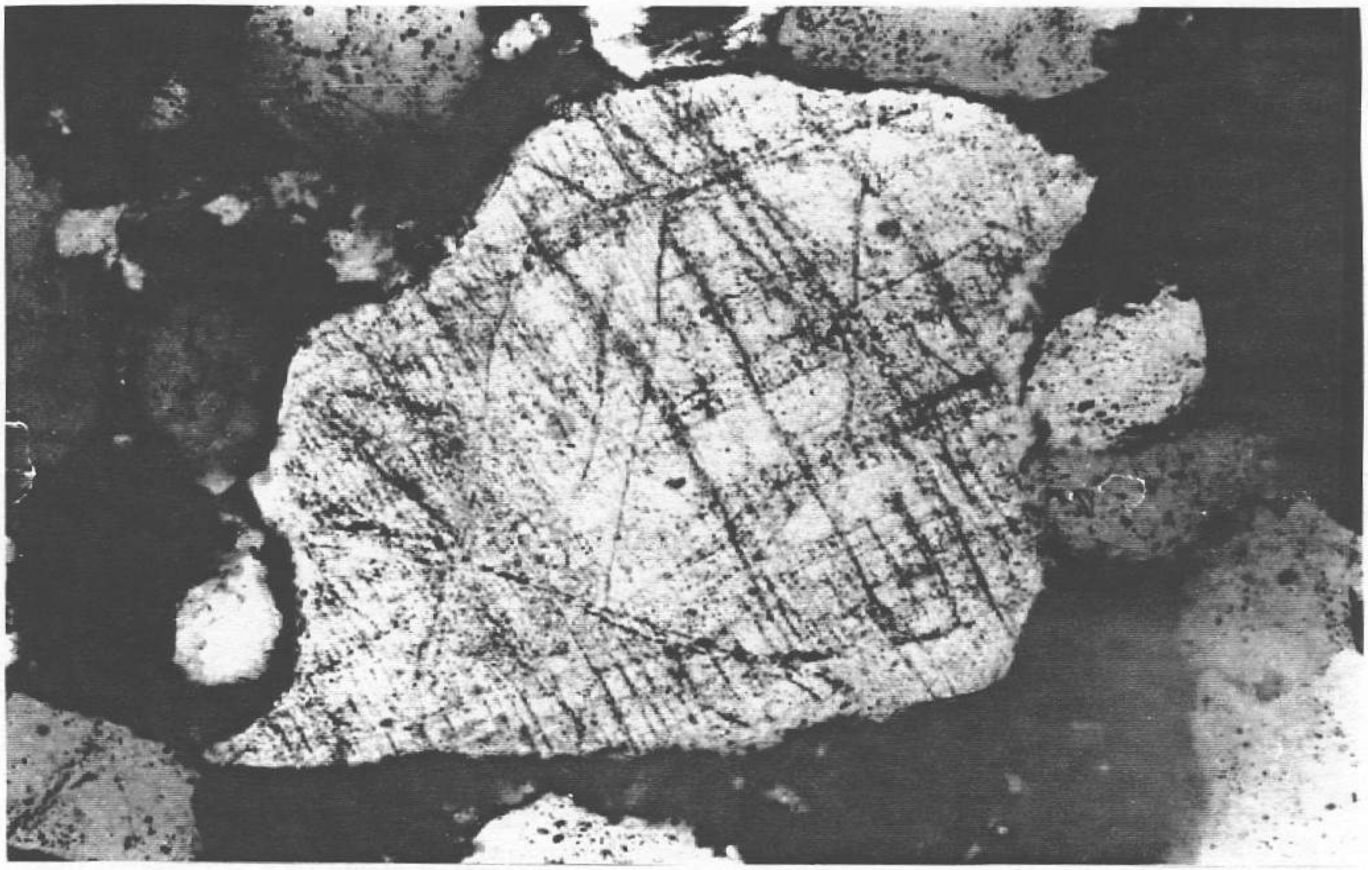

**Figure 4. Thin section from floor of crater 1 showing shocked quartz which has definitive parallel lines called planar deformation features.**

**Table 2. Rock samples collected from the impact craters on Sheep Mountain near Douglas, Wyoming.** Crater numbers correspond to Figure 1.

| Sample | Crater | Location | Date of Sampling |
|---|---|---|---|
| K1 | 1 | center | Jun 18, 1995 |
| K2 | 1 | west rim | Jun 18, 1995 |
| K3 | 1 | south flank | Jun 18, 1995 |
| K4 | 1 | 200 feet north of crater | Jun 18, 1995 |
| H1 | 4 | 200 feet south of crater | Dec 8, 1995 |
| H2 | 1 | south rim | Dec 8, 1995 |
| H3 | 1 | center | Dec 8, 1995 |

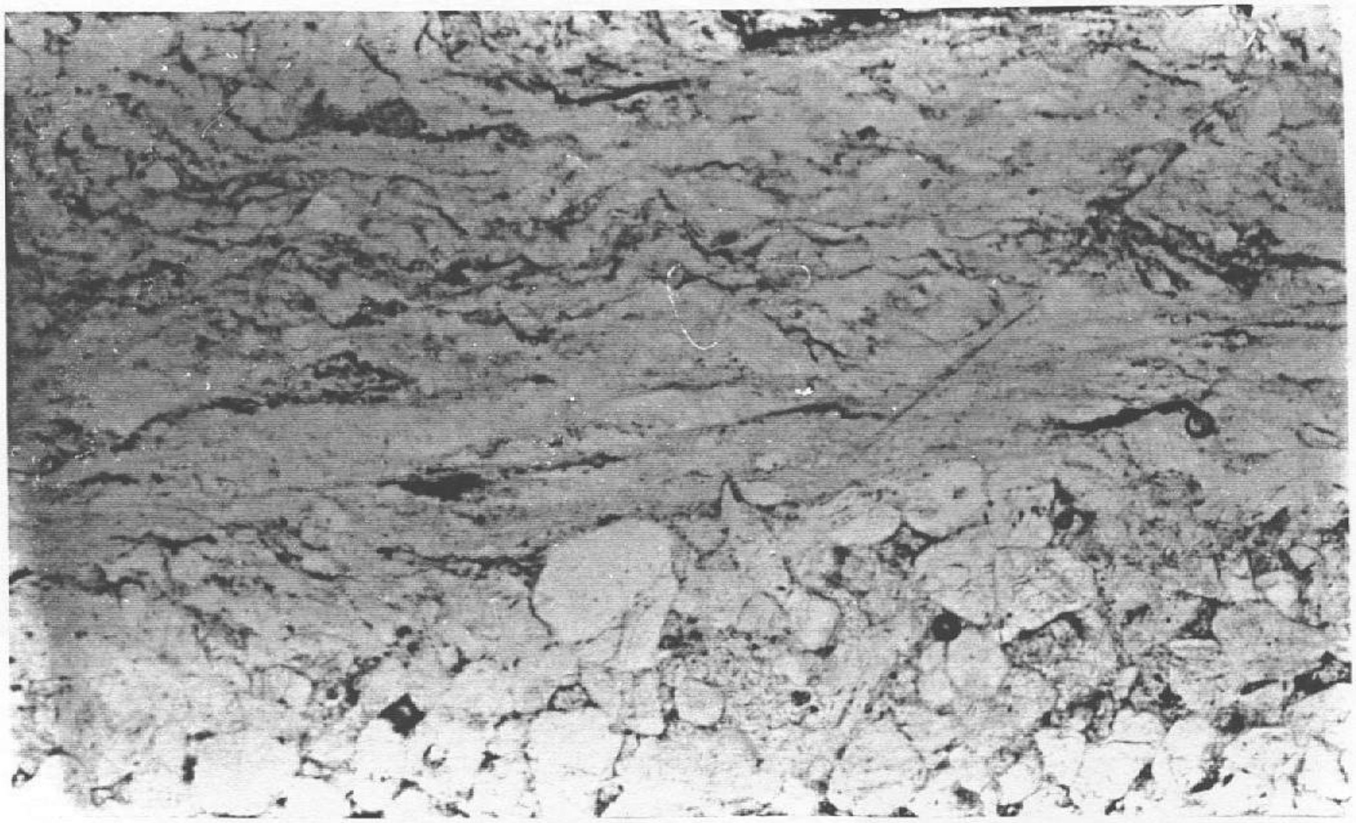

**Figure 5. Thin section from a crater floor showing brecciated clasts in a laminated, fine-grained cataclastic quartz matrix.**

cataclastic quartz matrix. The cataclastic quartz matrix exhibits mild but definitive preferred orientation of grains which is indicative of crystal-plastic deformation processes. These petrofabric features are indicative of extreme pressures, with the shocked quartz being associated only with the highest energy environments. Together these features can be taken as conclusive evidence for an impact, because they are isolated within an otherwise mildly deformed tectonic environment.

## DISCUSSION

The evidence assembled in this study reveals that the craters on Sheep Mountain are small meteorite impact craters. The geometric form of the features is consistent with small impact craters, especially the upturned and stratigraphically thickened rocks under the rims, and the thrusts faults which carried material outward from the centers. The two organized groups of maximum principal stresses deduced from conjugate shears reveal that two different yet superimposed stress regimes deformed the rim rocks. These are interpreted here as stresses associated with the outward directed motion of the rim rocks as the craters opened, and stresses parallel to the rings associated with rim contraction as the craters partially closed. The cataclasis and flowage petrofabrics as well as shocked quartz found in the thin sections from samples taken from the crater interiors are indicative of an impact. The presence of the shocked quartz is particularly convincing because the energies for its development far exceeds the energies associated with any other geologic processes known to have operated in the region in Phanerozoic time.

The spatial proximity and common age of the craters reveal that they represent impacts from a large body that fragmented prior to impact. Other craters may have been produced during this event but have been removed by erosion up-dip of the known examples, or remain buried by younger strata down-dip toward the northeast.

## CONCLUSION

The five craters found on Sheep Mountain south-southwest of Douglas owe their origin to impacts produced by a fragmented meteorite. The impacts date from the close of deposition of the Pennsylvanian Casper Formation.

## FUTURE WORK

Mineralogical work is required to determine if coesite or stishovite are present in the rocks samples collected from the craters. Coesite and stishovite are high pressure phases of quartz that have proven to be reliable evidence for high speed impacts.

## ACKNOWLEDGMENTS

The project was funded by a NASA Undergraduate Seed Money Grant awarded by the Wyoming Space Grant Consortium, University of Wyoming.

Local ranchers Bob and Georgia Garland generously provided housing for Kastning during the course of her field work. Keith Krugh of the University of Wyoming Department of Geology and Petrographic Consultants of Denver prepared the thin sections used in this analysis. Krugh provided crucial guidance in the interpretation of the thin sections.

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Shoemaker, E.M., 1963, Impact mechanics at Meteor Crater, Arizona: in, Middlehurst, B.M., and G.P. Kuiper, eds., The Solar System, v. 4: University of Chicago Press, p. 301-336.2017 Post Script: For additional information on Dr. Shoemaker's work, see: http://aipg-tx.org/memorials-carolyn/

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# Outcrop Photos of K- T Boundary 2017
# w/ Dr. Kent Sundell, Casper College, Wy.

DRAFT

# Wyoming K-T Boundary Thin-Sections

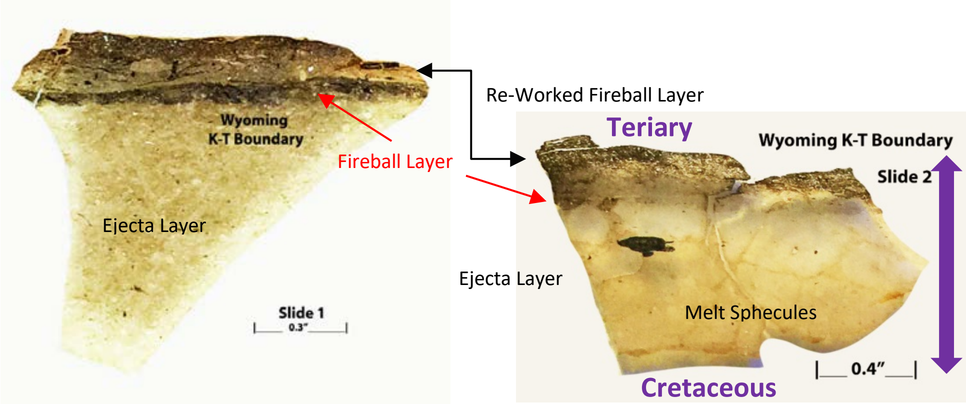
**A Preliminary Assessment**

**by**

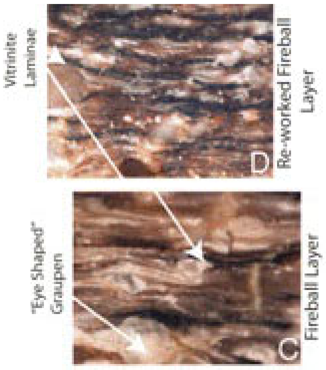
**Henry M. Wise, P.G., C.P.G. and Michael D. Campbell, P.G., P.H., C.P.G.**

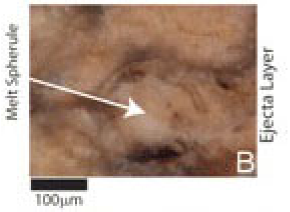
**April 21, 2018**

**Source of two samples below.**

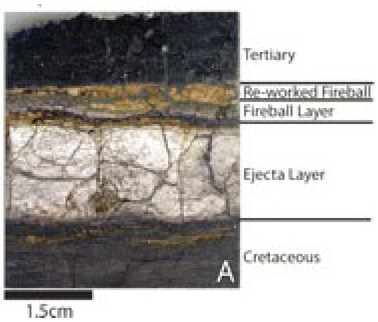


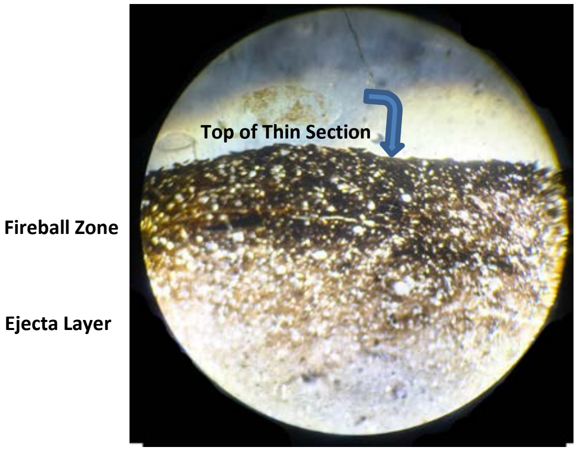
Information from Belchera, et al., (2009):



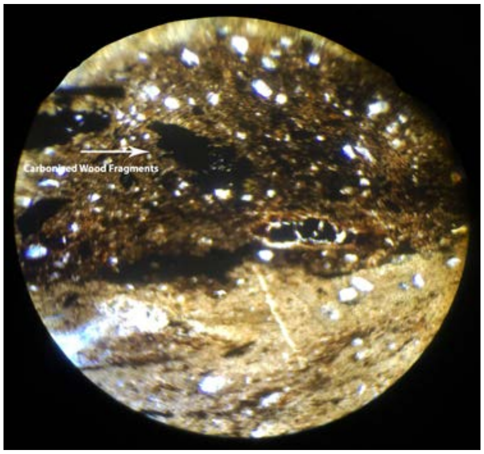


Note: Although Belchera, et al. reported on the PNA content of the carbonaceous material in their samples, our samples came from an area where coal/lignite are known just below the K-T boundary, which might explain why we found charred woody fragments incorporated in both the ejecta layer and in the "fireball" layer in our samples.



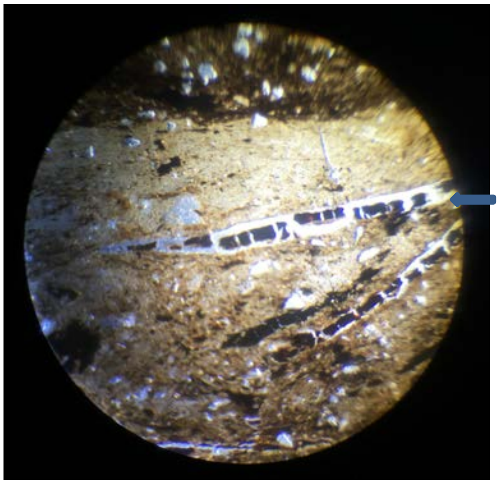


60X Plain Light



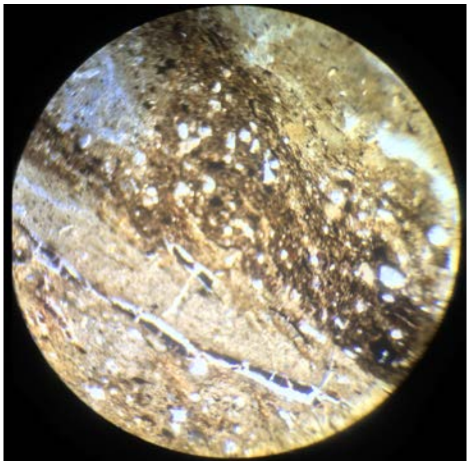
150X Plain Light

Fine-grained, angular and well-rounded quartz fragments (white grains, large and very small grains) with large and small fragments of carbonized wood fragments (vitrinite)). Carbonized wood fragments probably responsible for dark-brown color (upper) and part of air-borne ash.



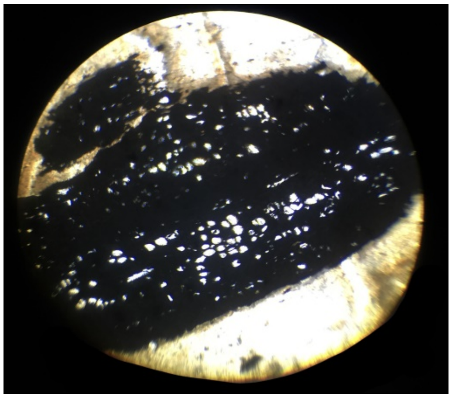
150 X Plain Light

Encapsulated carbonized wood fragments within silica (?) in ash zone.
Fine ash of carbonized wood (Vitrinite) in zone at top of section



150X Plain Light

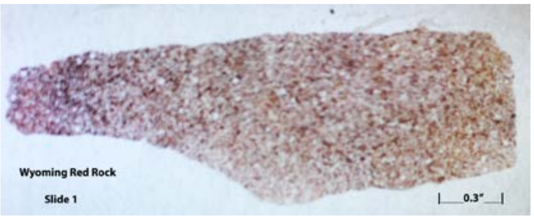
No indications of Shocked Quartz but Requires Crossed Nicols
to Confirm and Other Mineral IDs.

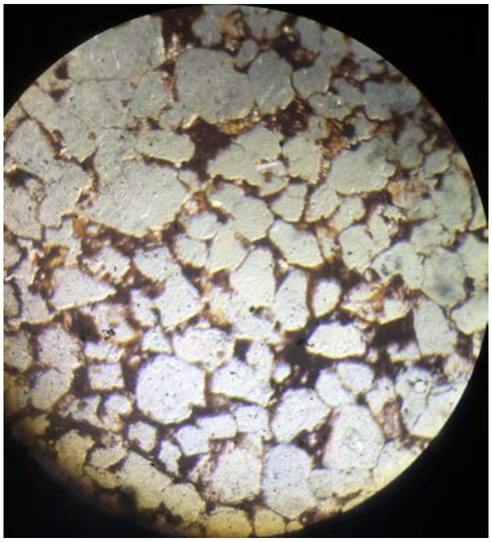


600X Plain Light

Carbonized Wood Fragment (Vitrinite).

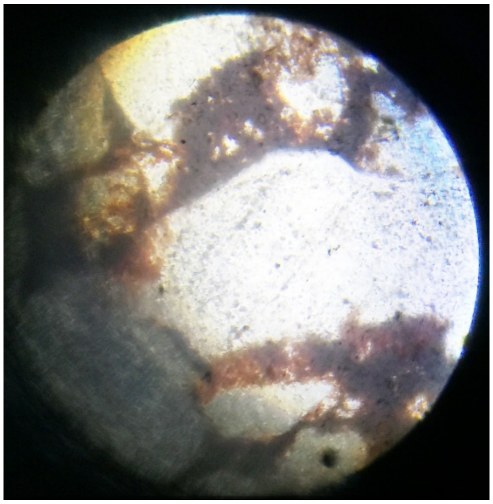
# Wyoming Red Rock Thin Sections





150X Plain Light

Slightly Rounded to Angular Quartz Grains with Ferruginous Fine-Grained Crystalline Particles Scattered over the Field in the Interstices of Dark Red to Yellow Color. May be Very Fine-Grained Siderite (?); See Figure Below.



600X Plain Light

Some Evidence of Shocked Quartz but Requires Crossed Nicols to Confirm.  See Ferruginous Crystalline Material.