Mammoths, Meteors, and Supernovae

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Summary of Events

<u>12,900 years ago</u>

- At least 35 mammal genera including Mammoths disappeared.
- Paleo-Indians disappeared from the Americas
- The Laurentide ice sheet over Canada suddenly failed
- Temperatures dropped by 10°
- Massive high temperature forest fires occurred
- A black algal mat formed over the landscape
- 500,000 shallow elliptical Bays formed over the Eastern US
- Extraterrestial materials were deposited directly over fossils

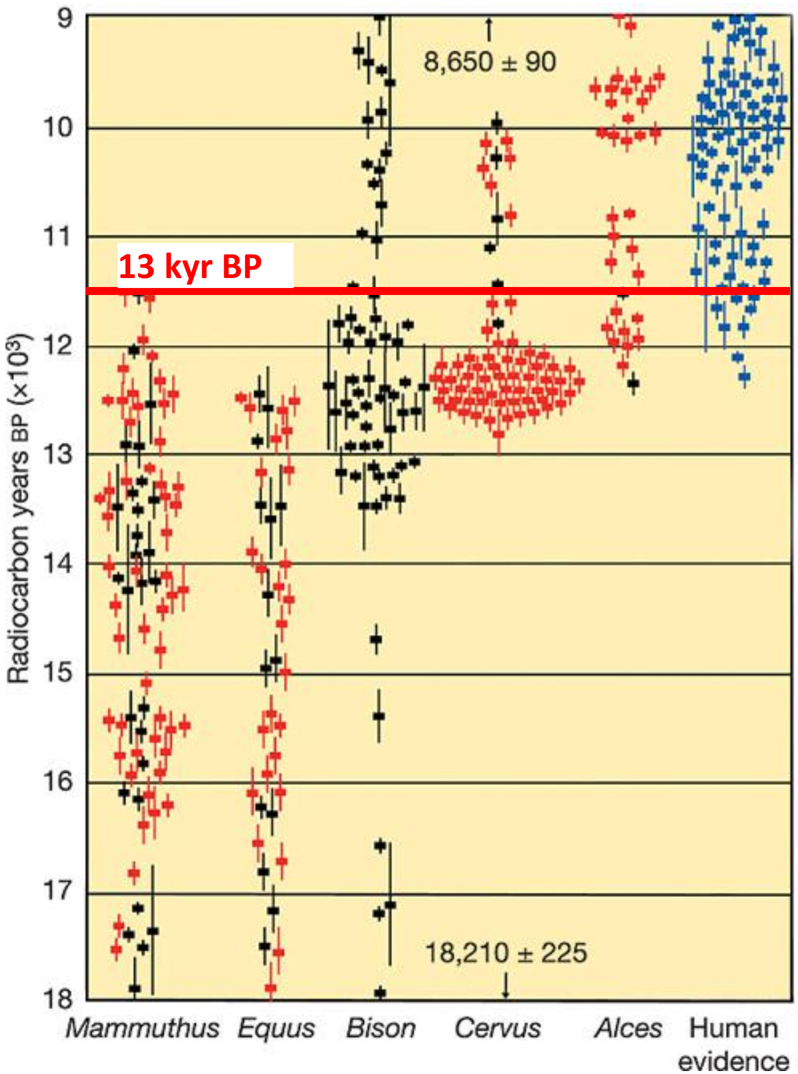
<u>35,000 years ago</u>

- Micrometeorites became embedded in Mammoth tusks
- Mammoths, bison, bears, and horses disappeared in Beringia
- Sithylemenkat Lake meteor crater formed in Alaska

<u>44,000-37,000-32,000-22,000 years ago</u>

- Supernovae exploded <250 parsecs from Earth
- 44,000 years ago megafauna extinctions occurred in Australia

Some populations were decimated in North America



Grayson D, Meltzer D (2003) *J Arch Sci 30:585–593.*

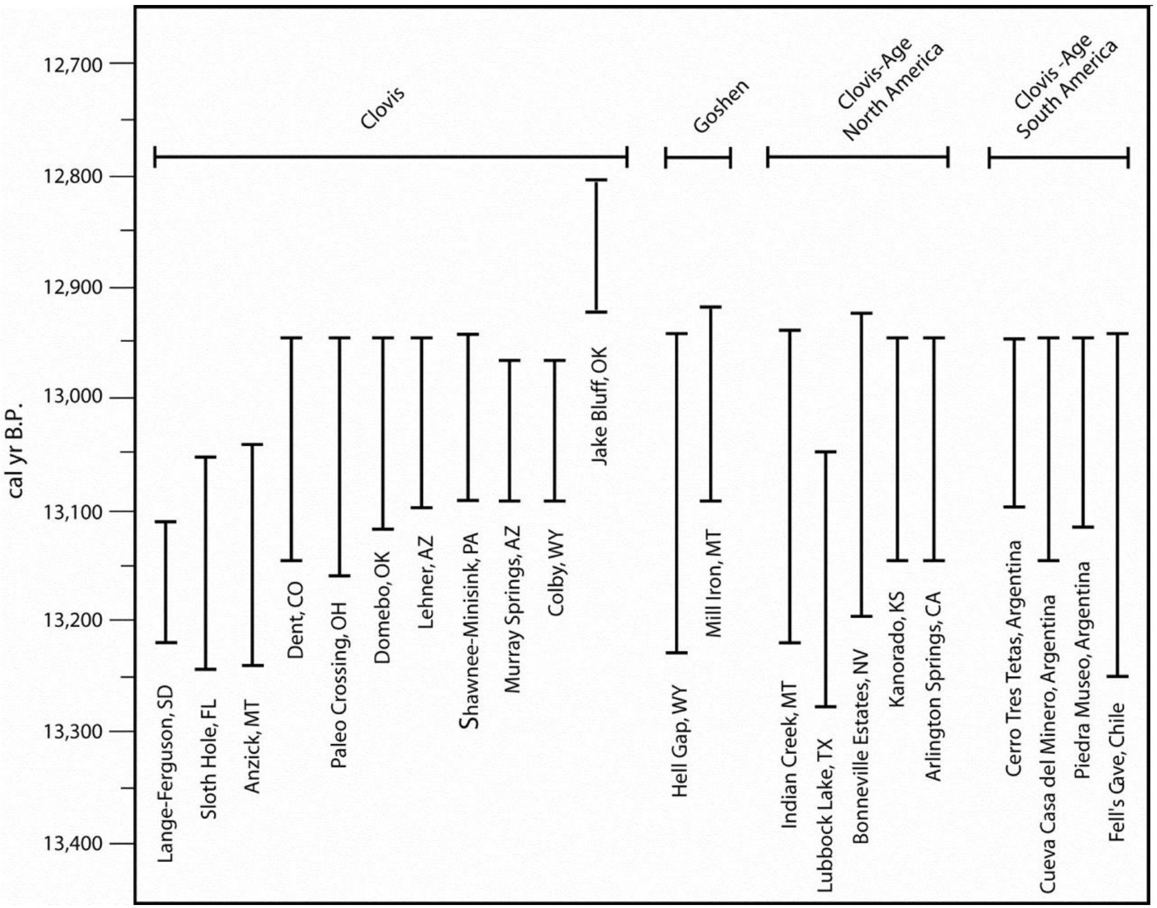
Extinct species

Giant Armadillo (2 species)	Tapirs
Simpson's Glyptodont	Peccary (2 species)
Ground sloth (4 species)	Camel
Short-face skunk	Llama (2 species)
Dhole (wild dog)	Mountain deer
Bear (2 species)	Stag moose
Large cats (3 species)	Pronghorns (3 species)
Giant beaver	Saiga (antelope)
Capybara (2 species)	Ox (2 species)
Aztlan rabbit	American Mastodon
Horses	Mammoths

Proposed explanations

- Human predation – how many Mammoth's can so few people eat? Who eats sloths?
- Climate change – these species survived climate change for millions of years.
- Disease – too many different species died at once.

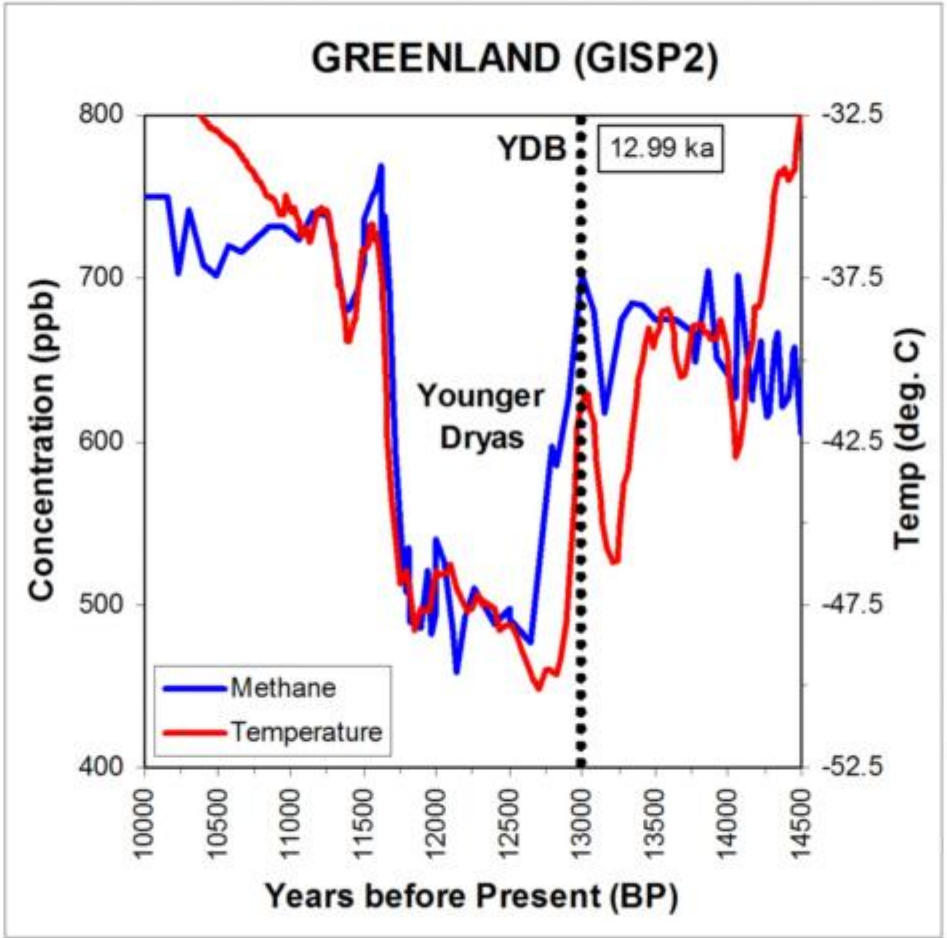
Paleoindians disappeared from North and South America



Range of Paleo-Indian dates in North and South America.

M.R. Waters and T.W. Stafford, Science 315, 1122-1126 (2007).

North America turned cold



Average temperatures suddenly drop in North America by 10°C

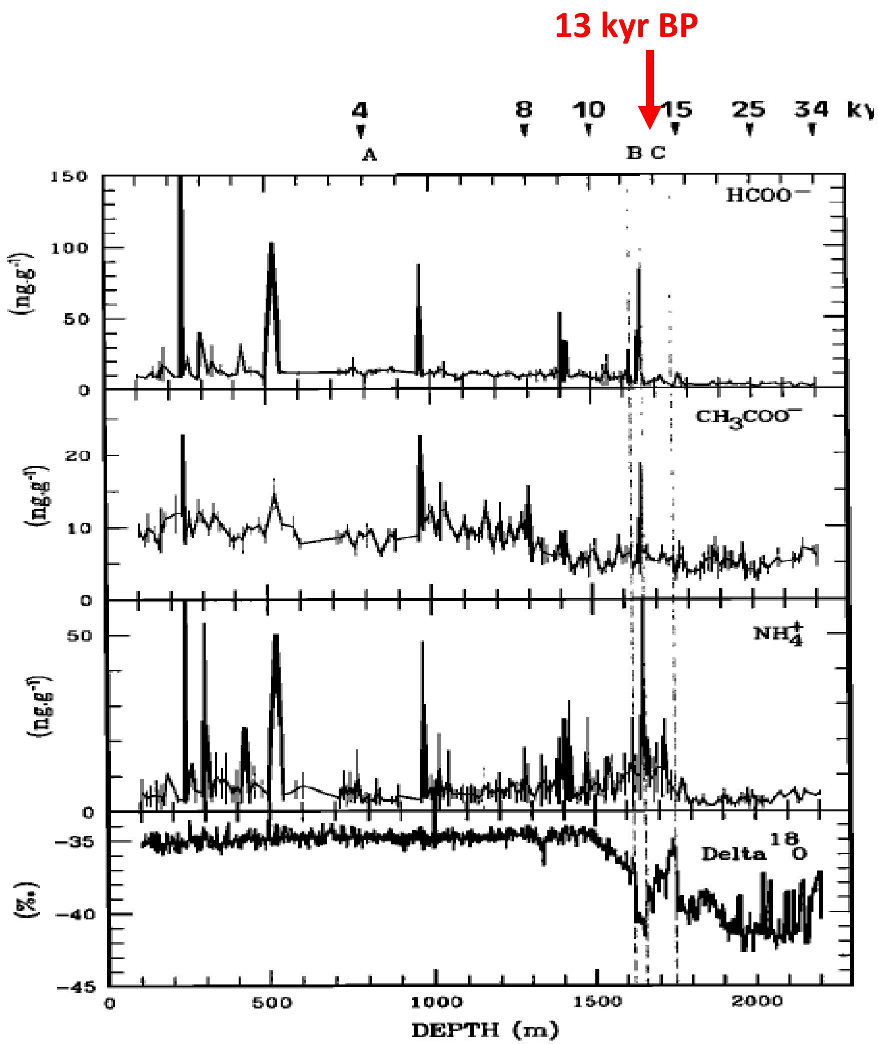
R.E. Taylor, C.V. Haynes, M. Stuiver, Antiquity **70**, 515 (1996) ; R.B. Alley, Quaternary Sci Rev. 19, 213 (2000).

The Earth suddenly cooled 13 kyr ago, staying cold for ~1300 years.

Conventional Explanation:

The Laurentide ice sheet collapsed sending fresh water into the North Sea upsetting thermohaline circulation.

Biomass Burning



Greenland ice core data

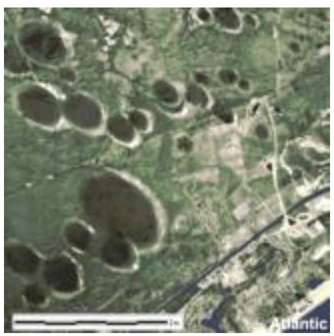
Formate ($HCOO^-$), acetate (CH_3COO^-) and ammonium (NH_4^+) concentration peaked in Greenland ice 12,900 yr ago.

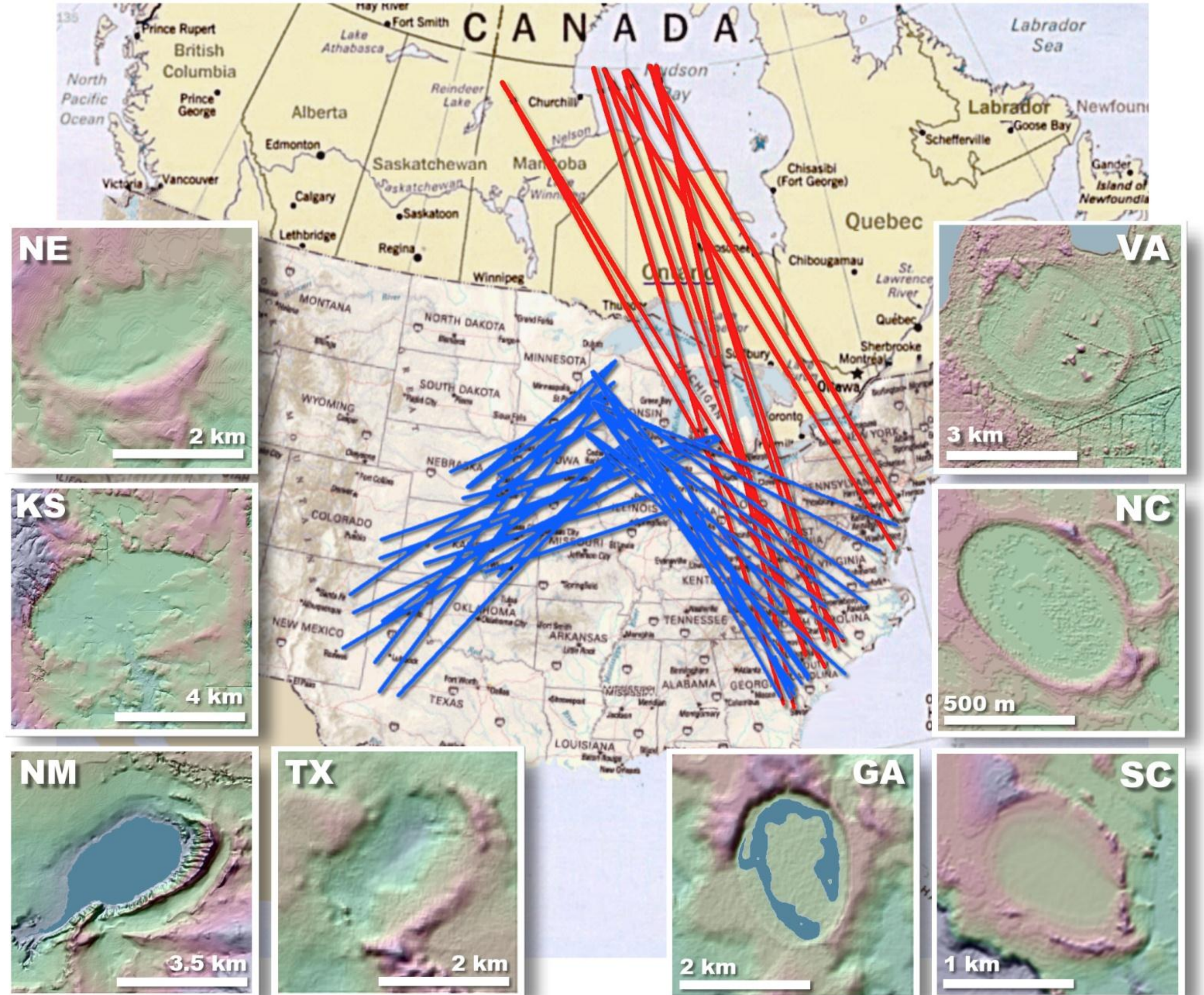
Ammonia highest in >100,000 years

These markers are evidence of high temperature burning.

M. Legrand and M. De Angelis, J. Geophys. Res. **100**, 1445-1462 (1995).

Orientation of Carolina Bays and possible related bay formations



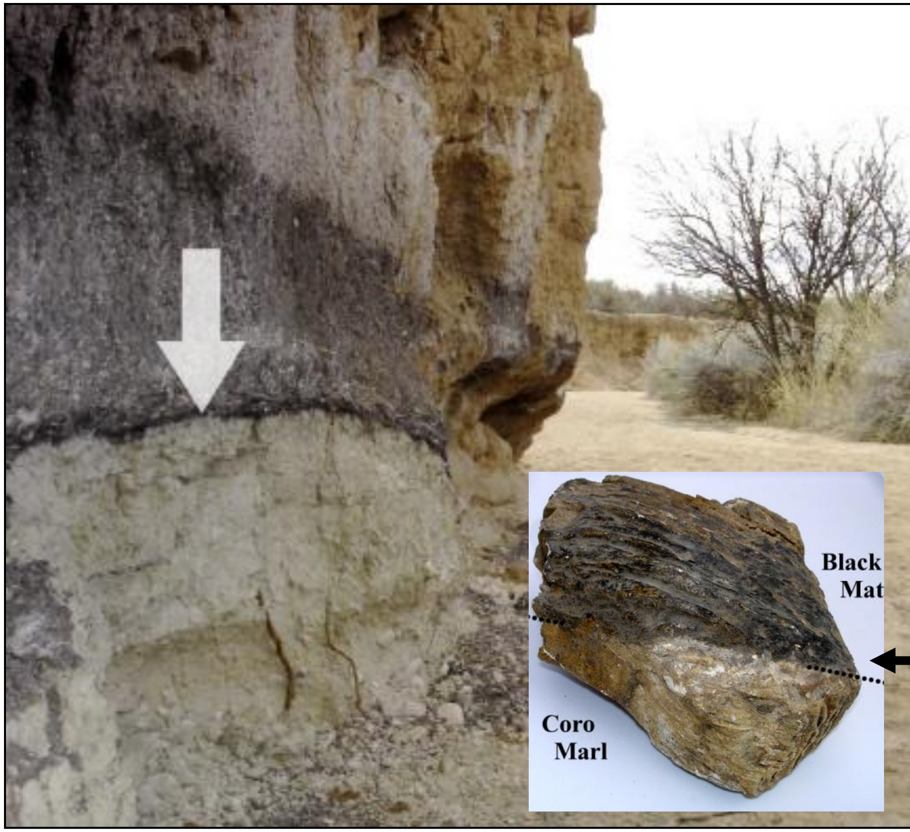


DEM images of Carolina Bays.

≈500,000 bays NJ to FL with parallel major axes pointing to the Great Lakes region.

Fewer western bays.

A "black mat" forms 13,000 years ago



A black mat, beginning 13 kyr ago, is found at more than 90 Clovis-age sites across North America.

No evidence of megafauna or Clovis artifacts is found within or above the black mat.

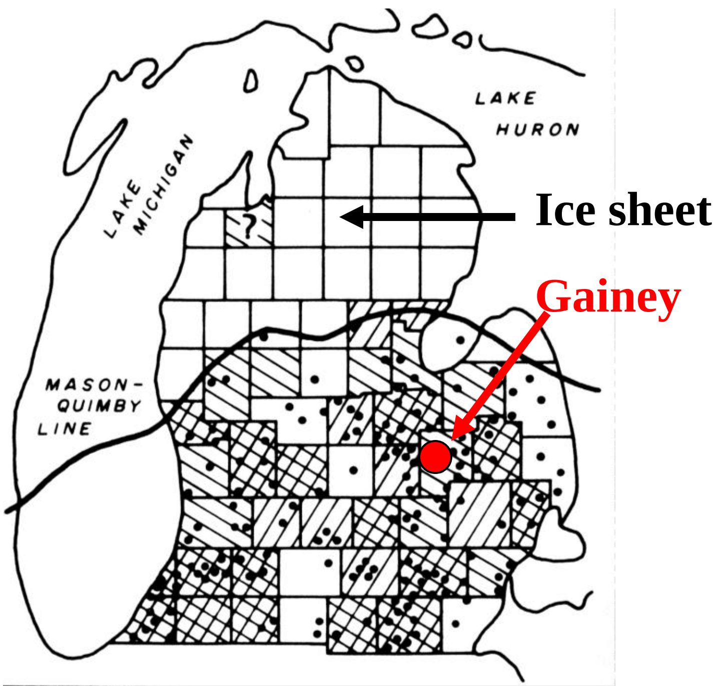
The black mat at Murray Springs, AZ was found draped directly over mammoth fossils.

The sudden extinction of the Pleistocene megafauna …..would be dramatically revealed by explaining that all were gone an instant before the black mat was deposited.

C. *Vance Haynes*
University of Arizona

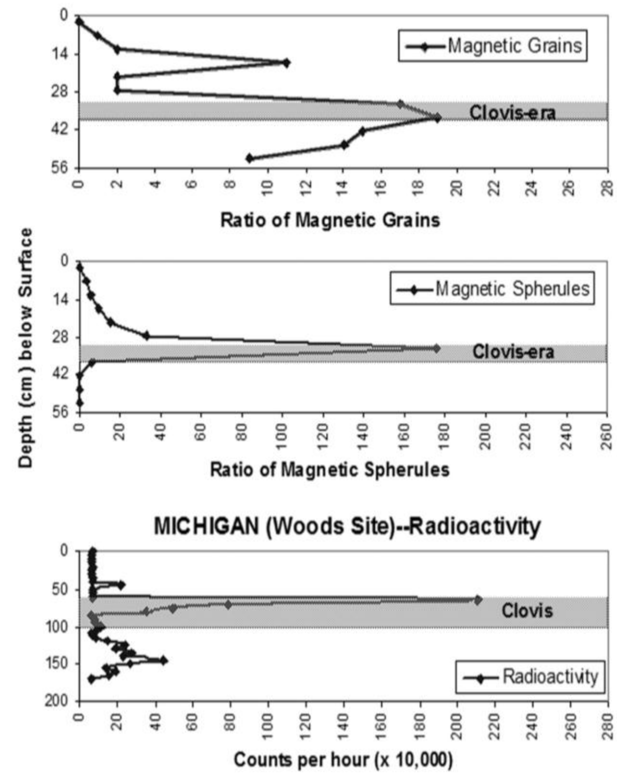
First Impact evidence from Gainey, MI

Archaeologist Bill Topping found at the Gainey, MI Clovis Paleo-Indian site



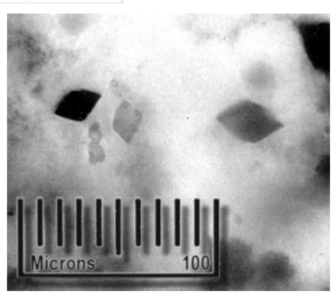
Magnetic grains and spherules

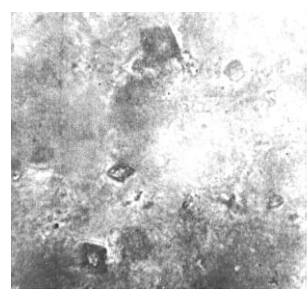
Excess Radioactivity



Etched particle tracks in Clovis chert (left).

100 MeV/A Fe ion tracks in modern chert (right), MSU.



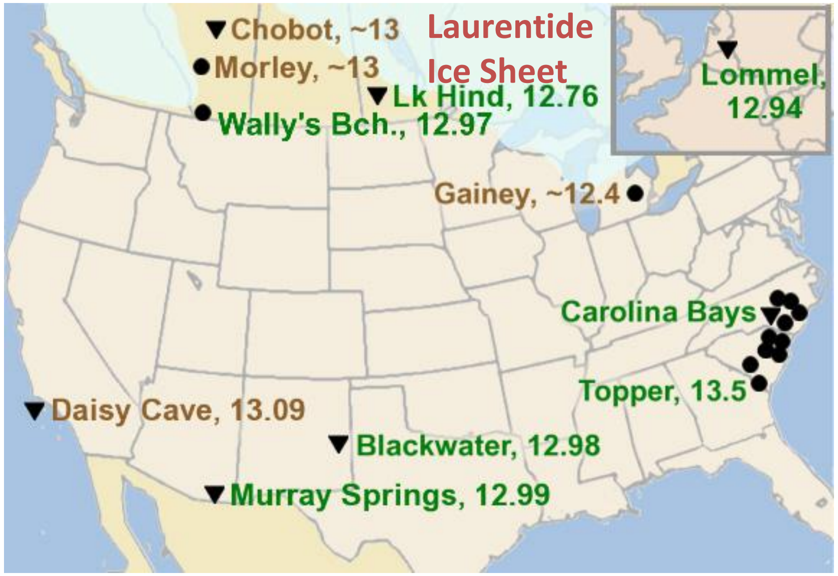


$^{187}Os/^{188}Os$ ratios, Sharma 2006

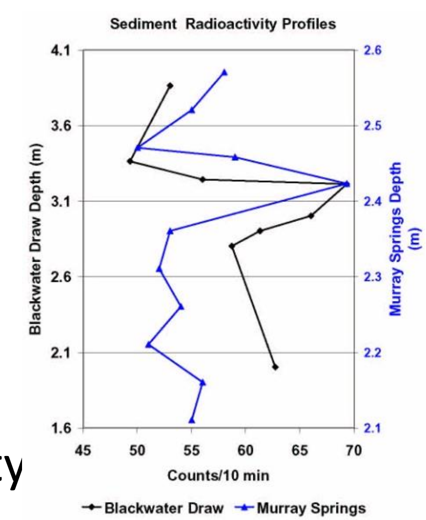
Infered that 12 ± 4 kyr ago the $^{187}Os/^{188}Os$ ratios of the Pacific Ocean crusts were suppressed due to a meteorite impact.

paper rejected by *Geology* because “no impact occurred at that time”.

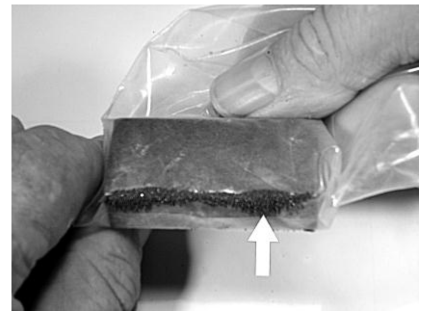
We gathered sediment evidence from 10 Clovis-age Sites and 16 Carolina Bays

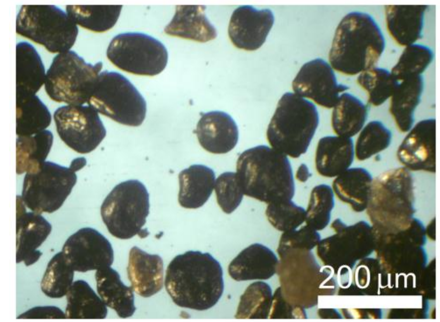


Geiger counter to measure radioactivity

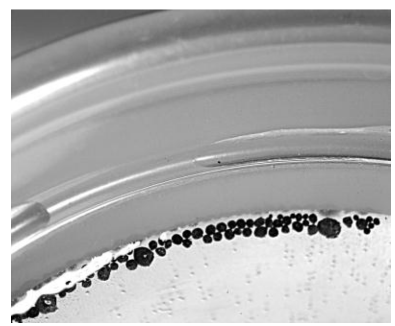


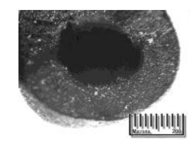
"High Tech experimental equipment"





Nd magnet to separate Magnetic grains and microspherules



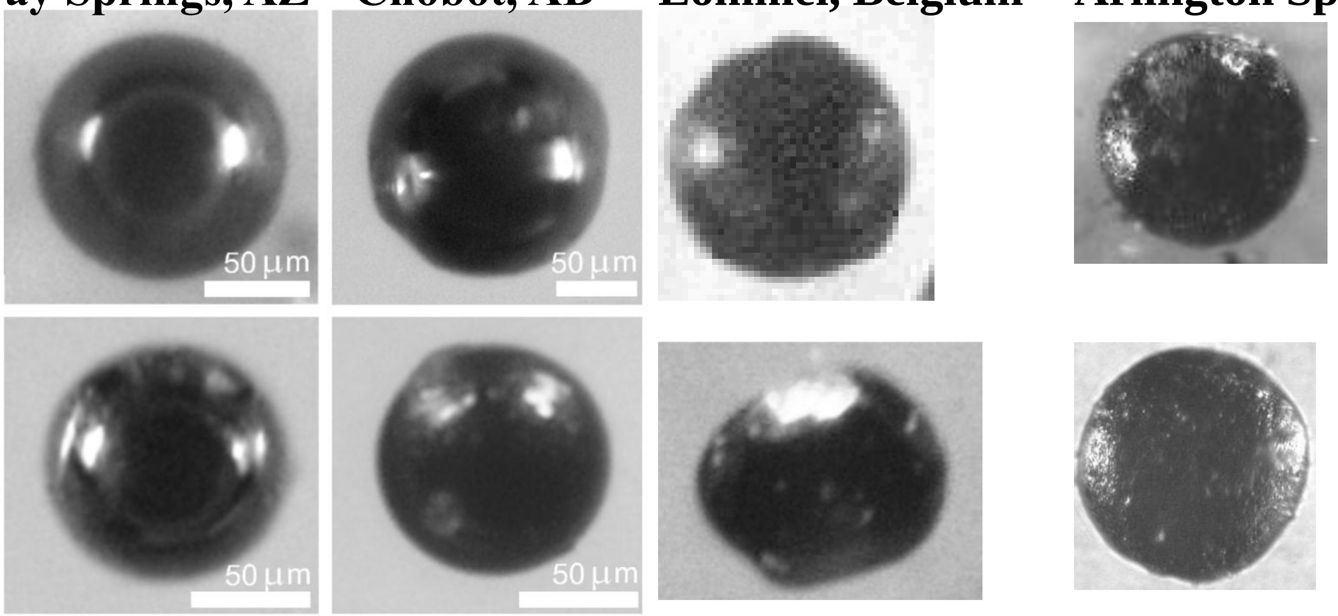


Flotation with water in a glass dish to separate carbon spherules, glass-like carbon, charcoal …

Samples collected by Allen West (US, Canada) and Han Kloosterman (Belgium)

Metallic Microspherules

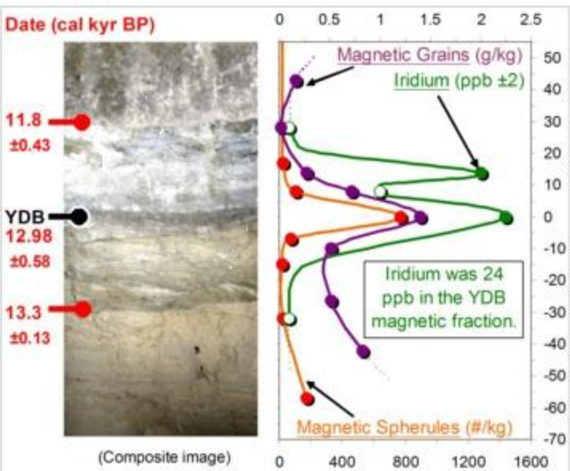
Murray Springs, AZ   Chobot, AB   Lommel, Belgium   Arlington Springs, CA



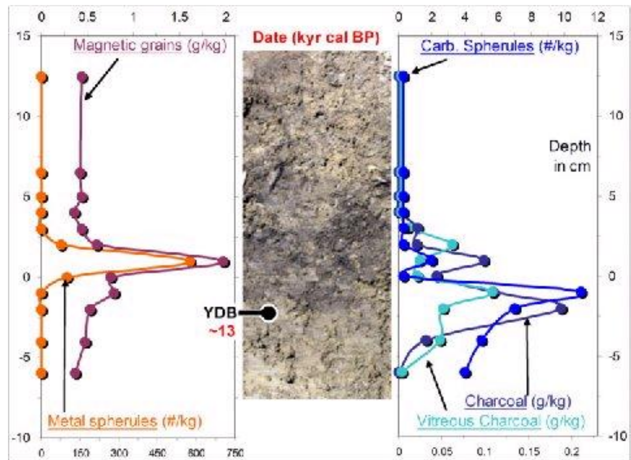
Gainey, MI   Topper, SC   Blackwater Draw, NM   Carolina Bay

Metallic (Fe/Ti) microspherules were found, only in the 12,900 year old YD boundary layer (YDB), at all sites.

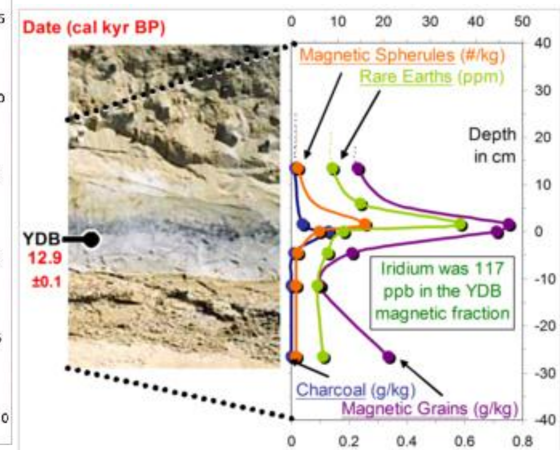
Impact markers peak near the YD Layer at all Clovis-age sites



Blackwater Draw, NM



Chobot, Alberta Canada



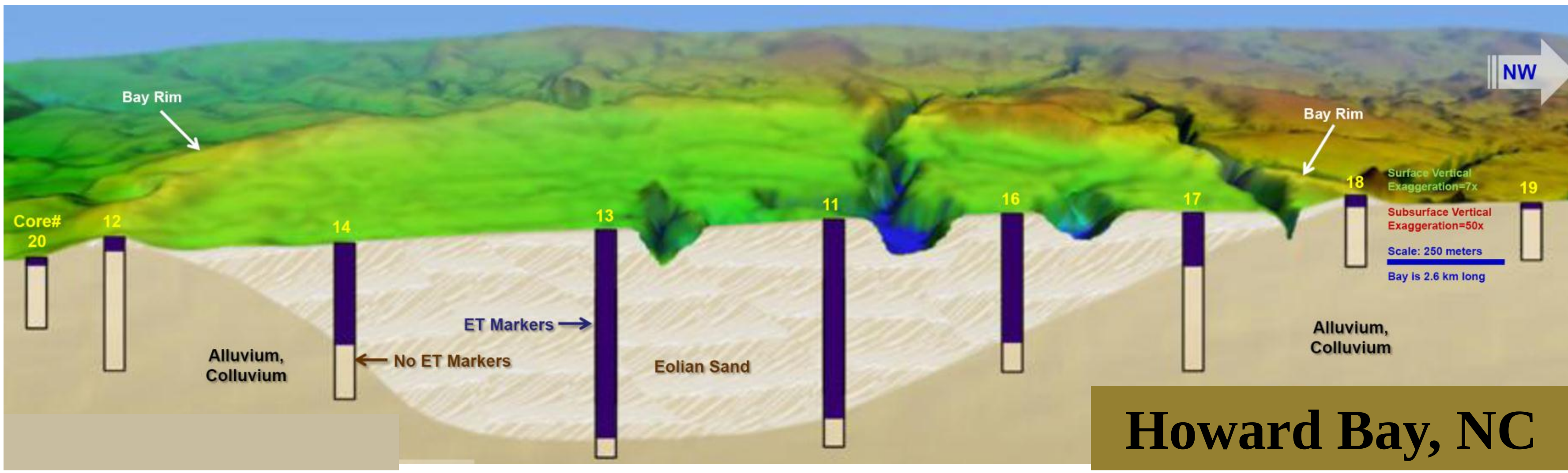
Lommel Belgium

Wally's Beach, Alberta Canada

Impact markers including very high concentrations of Ir were inside a 12.9 kyr old horse skull from Wally's Beach, Alberta were found among the tracks of mammoths, camels, and Clovis points

Carolina Bay Impact Markers

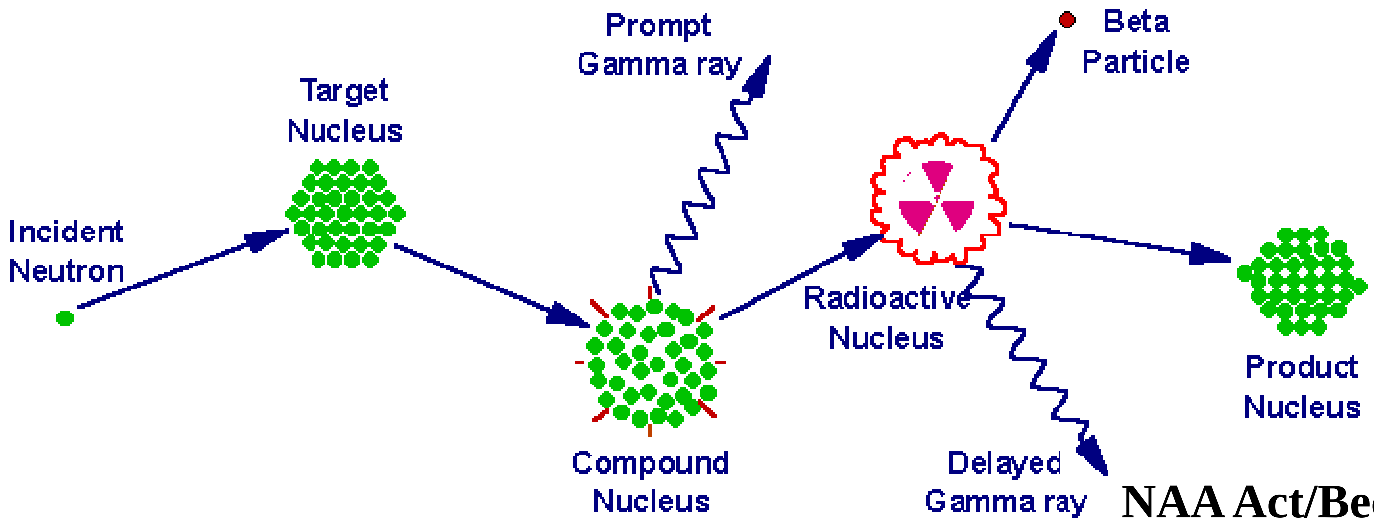
Magnetic microspherules, carbon spherules, and other impact markers are mixed throughout Carolina Bay sediments but not below.



Drawing courtesy of George Howard, Raleigh NC.

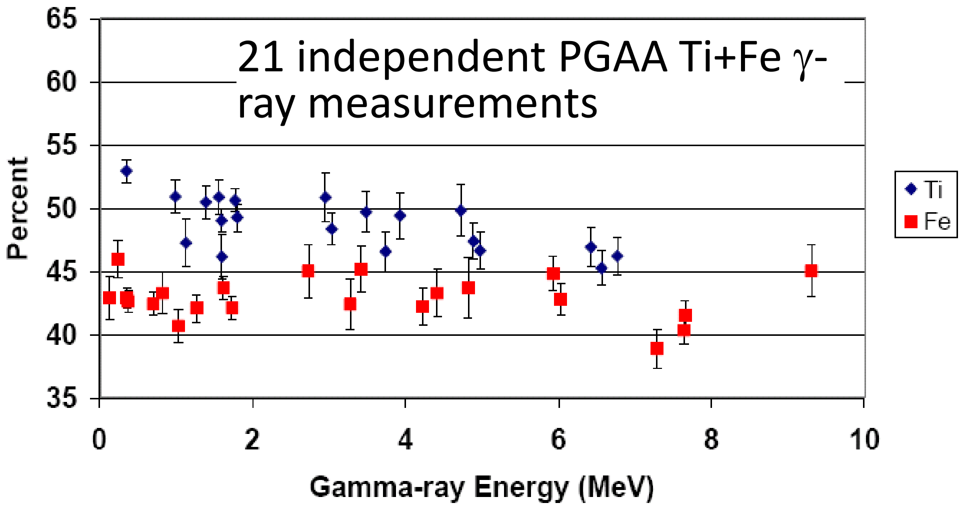
PGAA/NAA analysis of magnetic grains

PGAA Budapest



NAA Act/Becquerel Labs Canada

Analysis of Topper grain sample



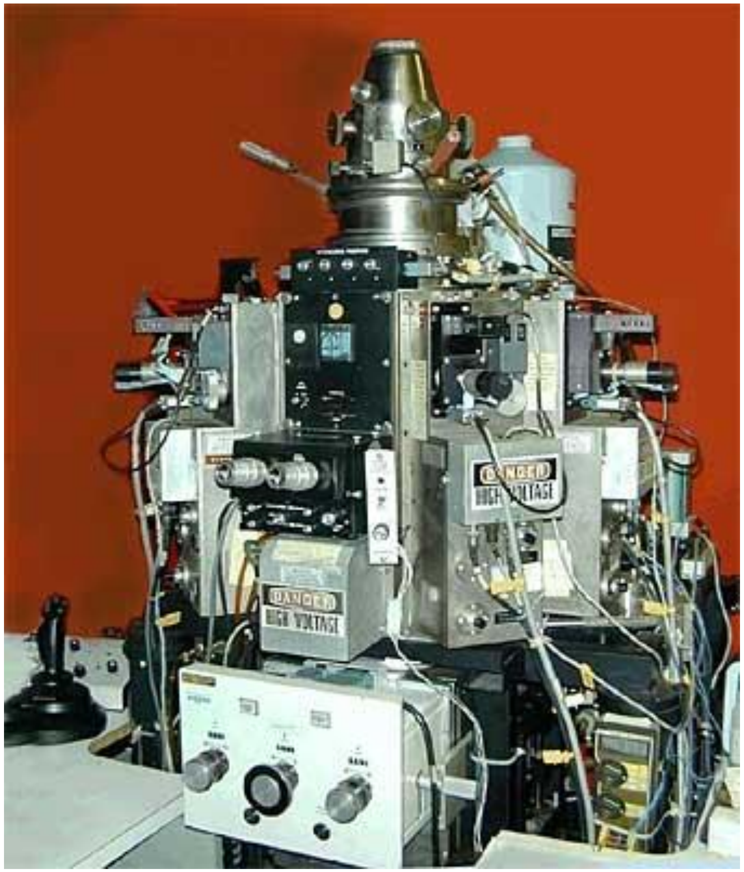
Prompt Gamma-ray Activation Analysis (PGAA) is sensitive to <0.1 mg/cm^3 of any element from H to U. NAA is very sensitive to selected trace elements.

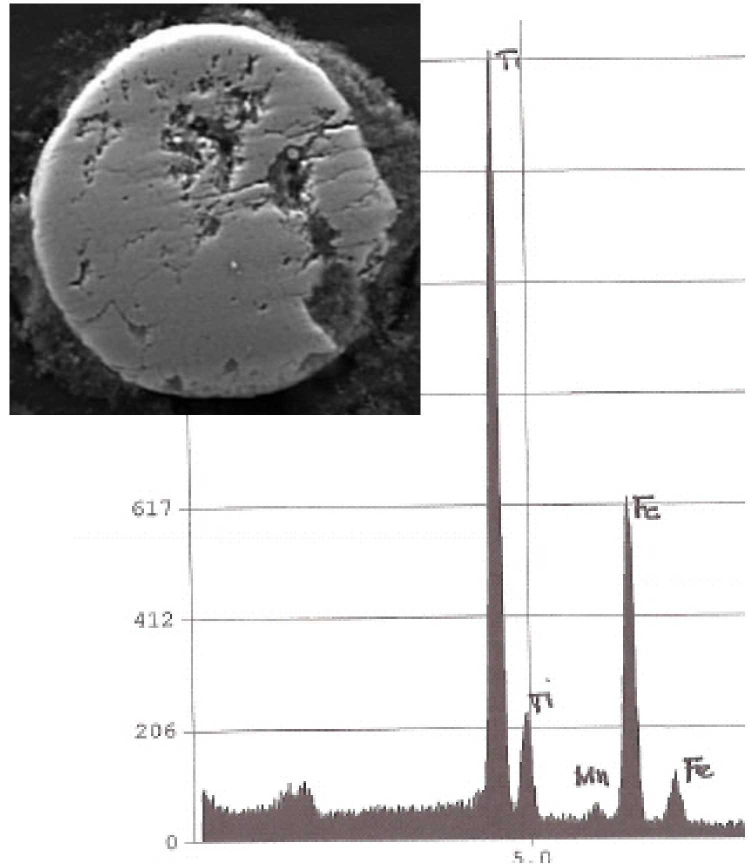
Bulk Analysis of Metallic Grains

PGAA/NAA Analysis of Metallic Grains									
Site	H_2O	MgO	Al_2O_3	SiO_2	CaO	TiO_2	MnO	FeO	Ir
	Wt.%								ppb
Gainey, MI	3.2	2.9	11	60	2.2	1.6	0.4	14	<2
Murray Springs, AZ	5.1	2.0	6.7	41	3.8	16	2.0	21	2
Blackwater Draw, NM	1.5	2.1	6.5	51	0.2	8.1	1.1	27	24
Chobot, AB	5.0		12	62	1.3	0.9	0.5	14	
Wally's Beach, AB	1.6		6.9	34	3.5	8.3	0.3	41	51
Topper, SC	0.7	0.4	1.9	5		49	0.2	43	2
Lommel, Belgium	0.8	1.3	1.4	51	1.3	21	1.4	33	117
Crustal		2.5	15	67	3.6	0.6	0.1	5	0.02

PGAA/NAA elemental analysis of more than 45 elements was measured in over 200 samples. The high Ti concentrations are unusual for meteoritic material, although the high Ir concentrations are clearly extraterrestial.

SEM/XRF analysis of magnetic grains and microspherules





Scanning electron microscope x-ray fluorescence (SEM/XRF) analysis of microspherules performed at Cannon Microprobe (Seattle) and at USGS Menlo Park. Analysis of a sliced Ti-rich Gainey microspherule is shown.

Analysis of Metallic Microspherules

Microspherules and magnetic grains are rich in Ti.

The high Ti/Fe ratio is not found in terrestrial sediments or meteoritic material.

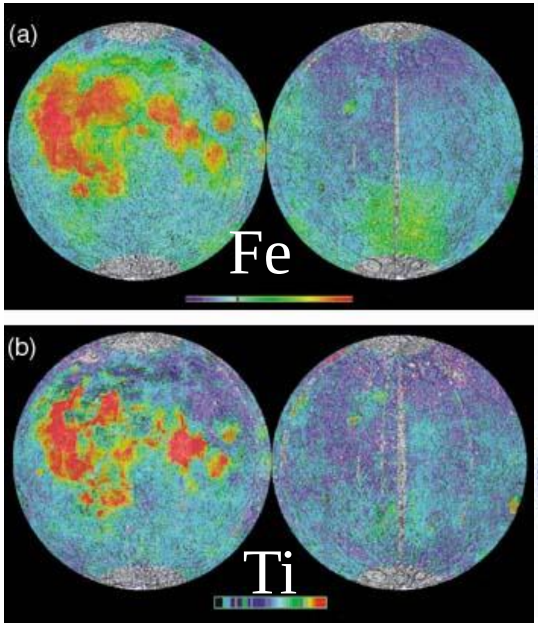
The only comparable Ti/Fe ratio was found in lunar Procellarum KREEP Terrane (Apollo 12).

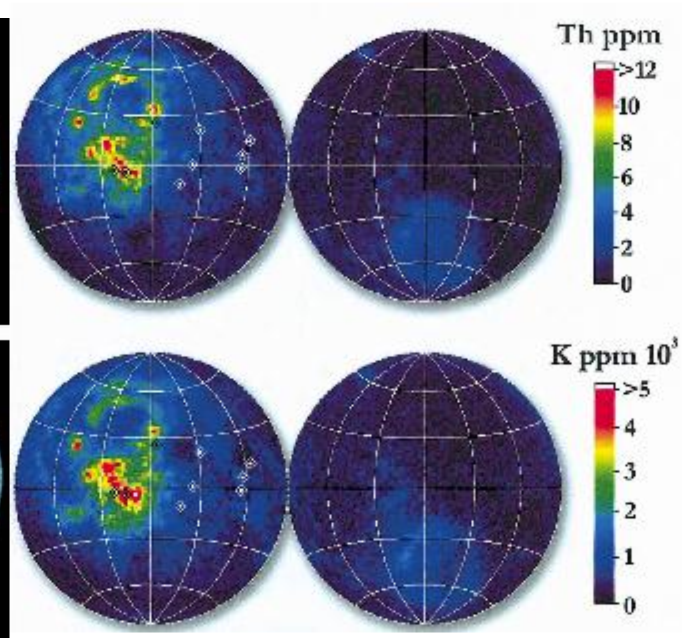
XRF Analysis of Microspherules (Wt.%)

Site-sample	Al_2O_3	SiO_2	TiO_2	FeO	MnO	Ti/Fe
Blackwater-1	3.7	5.8	13	74	1.7	
Blackwater-2	2.3	3.1	53	37	3.5	
Gainey-1	2.7	5.1	0	92		
Gainey-2	24.8	55	2	18		
Gainey-3	2.9	4.0	68	25	0.1	
Gainey-4	6.4	40.1	25	7		
Gainey-5	1.9	3.7	29	64	1.0	
Morley-1	2.7	4.5	47	44	1.7	
Morley-2	3.0	4.6	40	50		
Morley-3*	1.7	1.9	0	84		
Morley-4	3.4	11.5	0	84		
Lommel-1			74	16		
Lommel-2			54	11		
Lommel-3			74	16		
Spherule Ave.	**5.0**	**12.7**	**34**	**44**	**0.7**	**0.77**
Grain Ave.	**6.1**	**44**	**22**	**30**	**0.9**	**0.73**
Crustal	**15**	**67**	**0.6**	**5**	**0.1**	**0.12**
Ocean trench	**10**	**59**	**0.5**	**7.6**	**2.2**	**0.07**
LOIB						**0.20**
KT layer	**15**	**70**	**0.3**	**4.5**	**0.01**	**0.07**
PT layer	**9**	**24**	**0.45**	**2.3**	**0.02**	**0.20**
CI Chondrite	**1.6**	**23**	**0.07**	**24**	**0.3**	**0.003**
KREEP	**9**	**14**	**12**	**19**		**0.63**

* Also contains 12% Ni

Lunar Procellarum KREEP Terrane



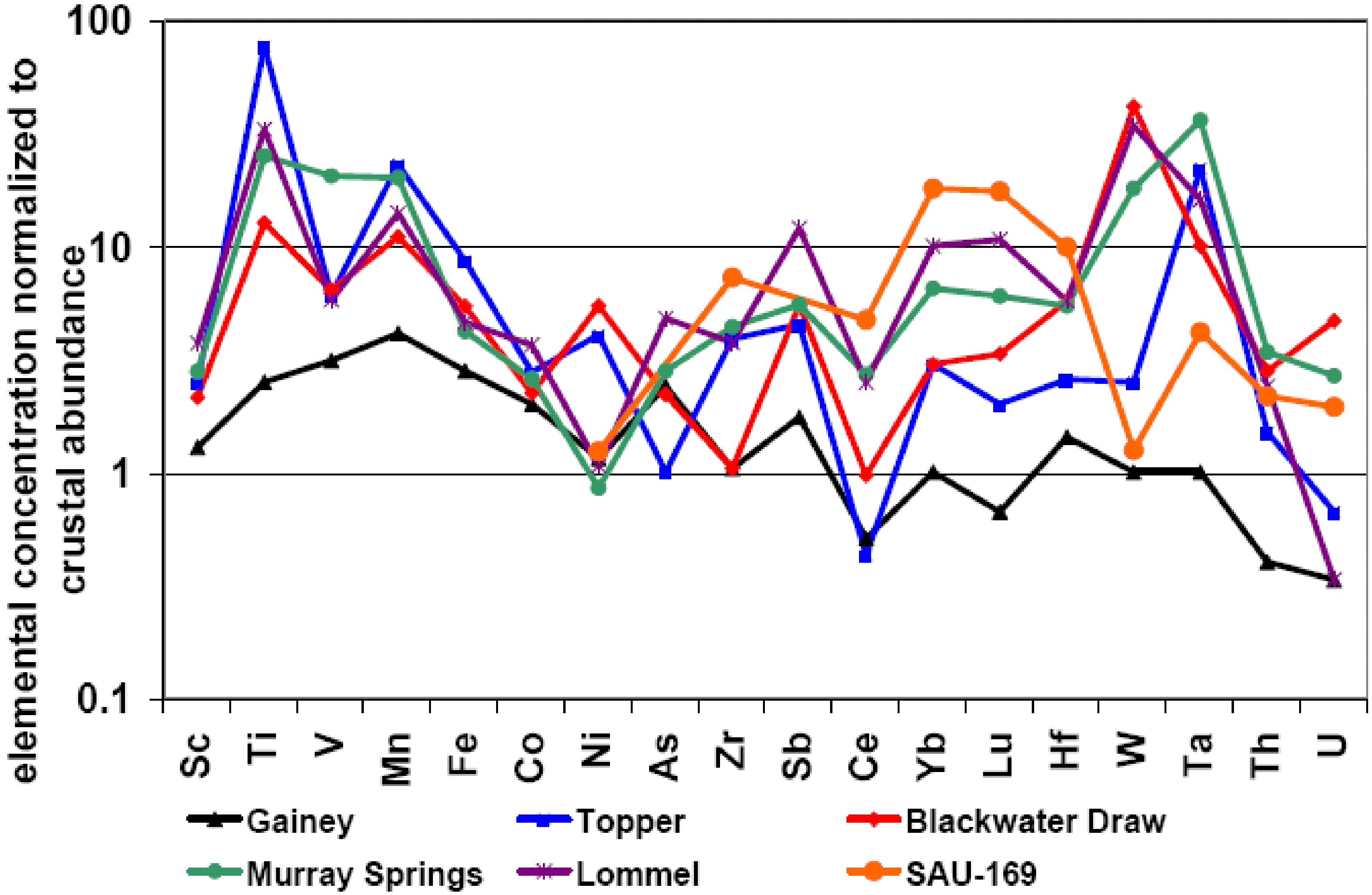


SAU 169

Lunar Procellarum KREEP Terrane is a small area of the moon with high FeO (≤20%), TiO2 (≤15%), Th (>6 ppm) and K, rare earth, P, and other "incompatable" element (KREEP) concentrations.

SAU 169 is the only lunar meteorite believed to come from this region. It left the moon <400 ka ago and fell to earth ≈10,000 years ago, possibly at the time of the YD impact.

Chemistry of the Ejecta Layer

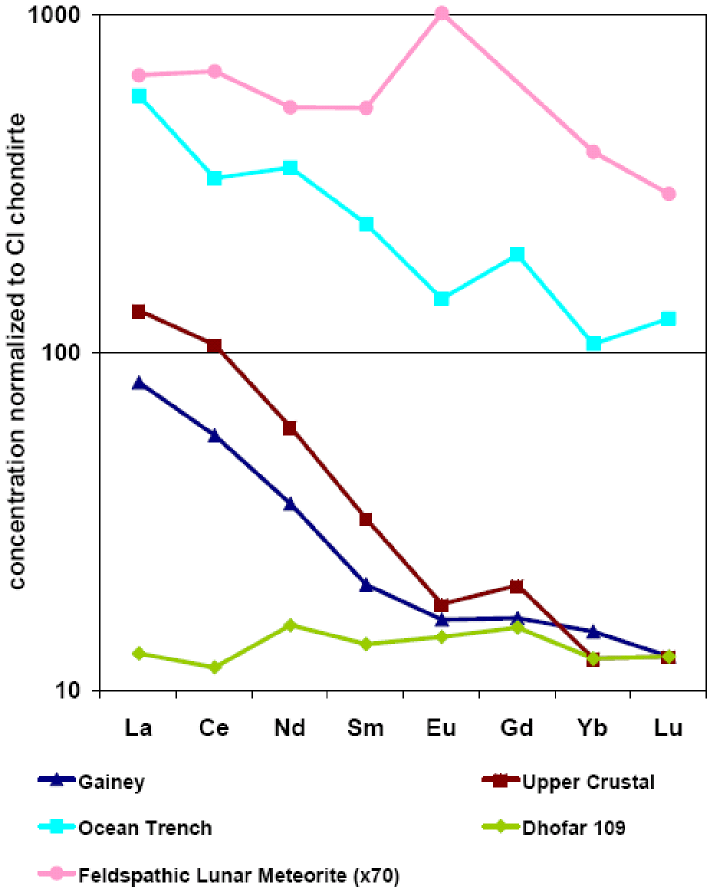


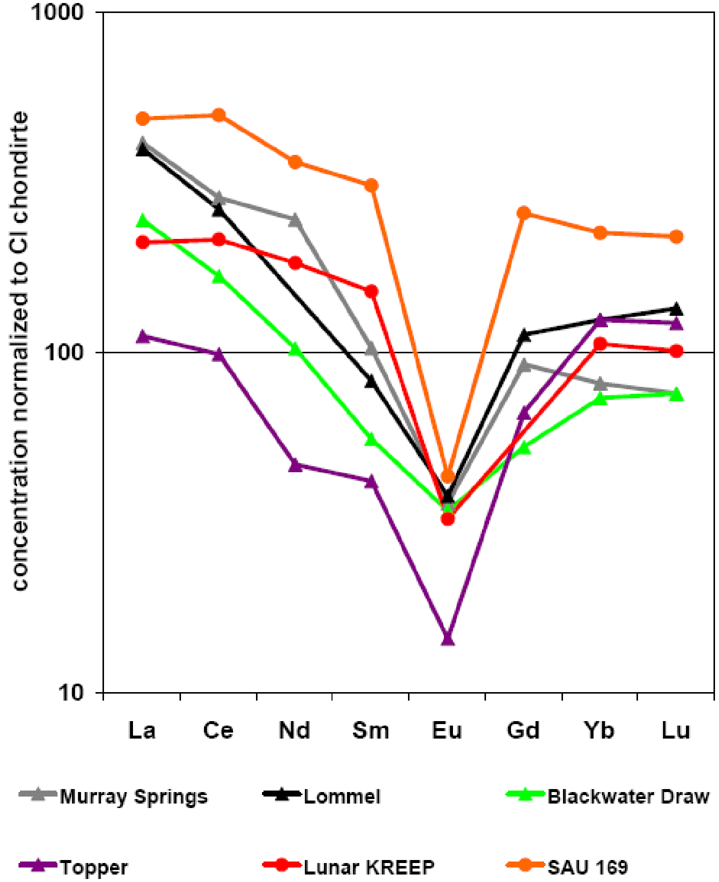
The Gainey ejecta (black) have terrestrial composition.

Other ejecta are similar to lunar KREEP meteorite SAU-169 (orange).

Conclusion: Gainey is near the impact site where low-velocity terrestrial debris fell. Other sites contain high-velocity, lunar-like impactor ejecta.

Chemistry of the Rare Earth Elements (REES)

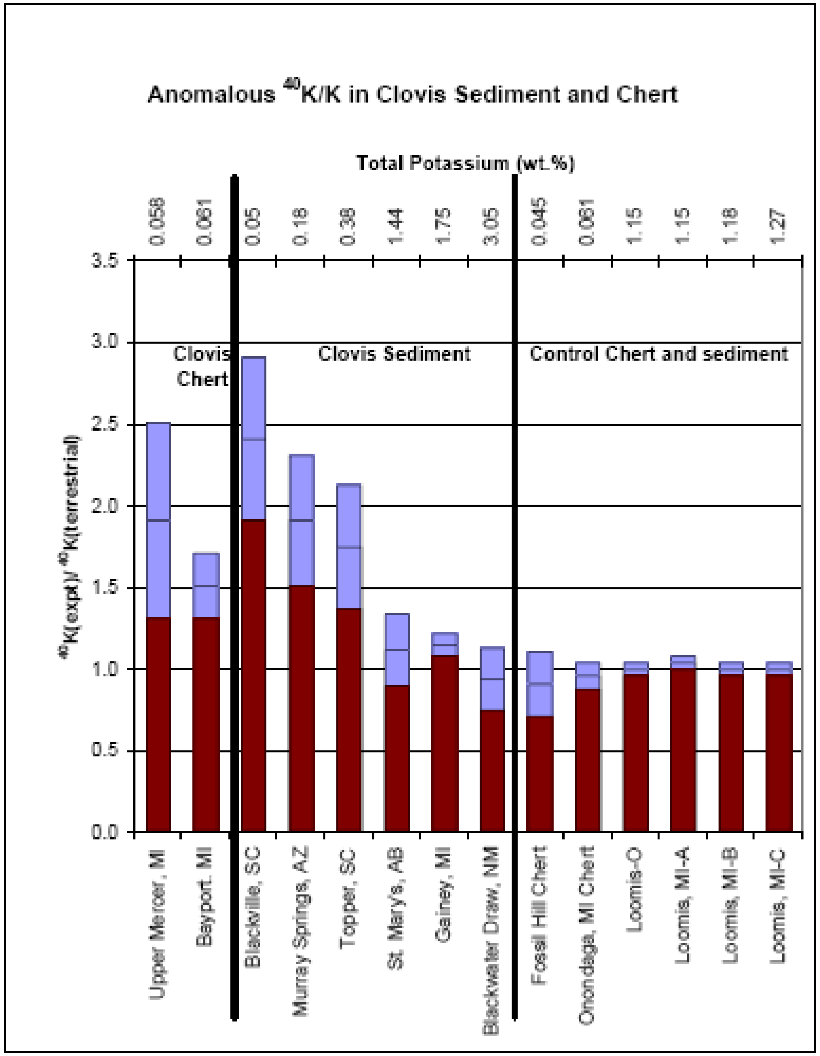




CI chondrite-normalized REEs from Gainey (black) are similar to crustal sources (brown).

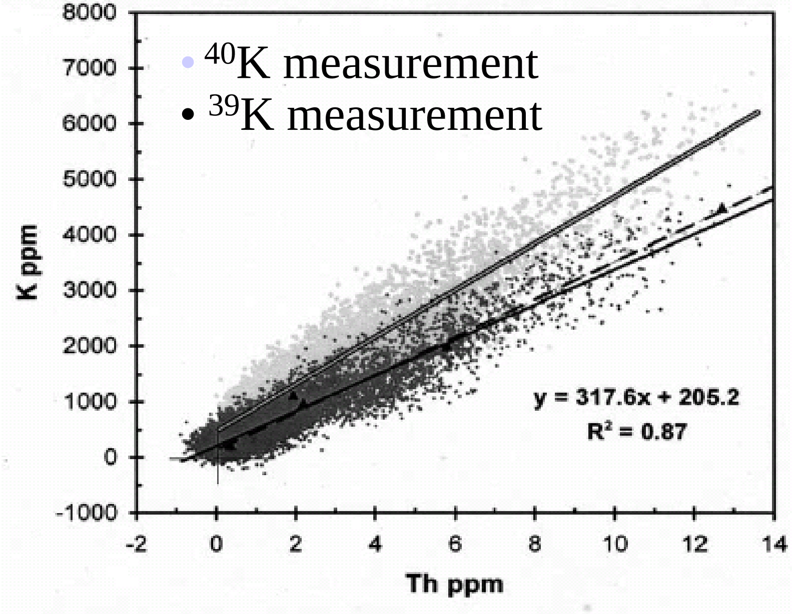
Ejecta from other sites have a negative Eu anomaly similar to lunar KREEP (red) and lunar KREEP meteorite SAU-169 (orange).

Anomalous ^{40}K abundance



Source	$^{40}K/K$
Terrestrial (IUPAC)	0.0117±0.0001%
Microspherules (Oceanic)	0.016–0.020%
Fe Meteorites (Voshage)	1.6 - 18.9%
Cosmic rays (Connell)	31%

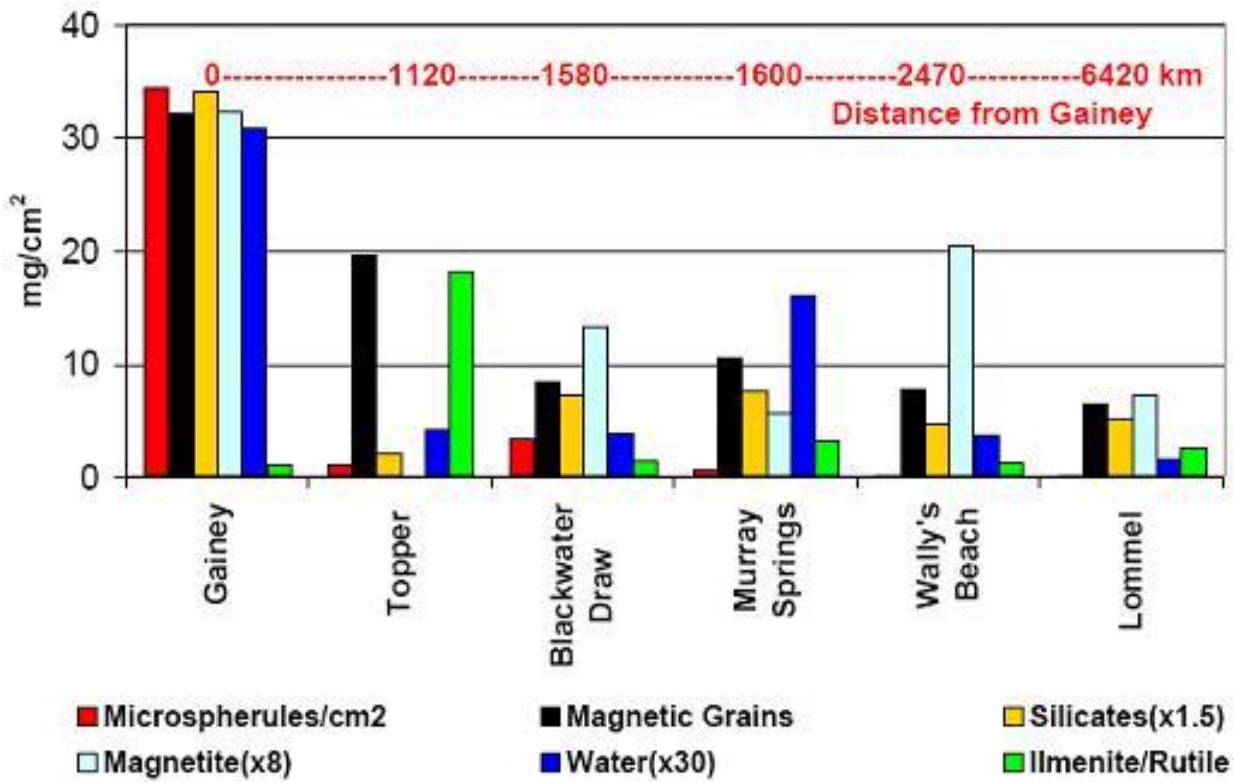
Lunar Sediment Measurements



^{40}K abundance measured by γ-ray counting at the LBNL Low Background Facility (Al Smith). Total K abundance measured by PGAA/NAA.

Similar enrichments are seen in oceanic microspherules and possibly in lunar sediment. ^{40}K is highly enriched in Fe meteorites and cosmic rays.

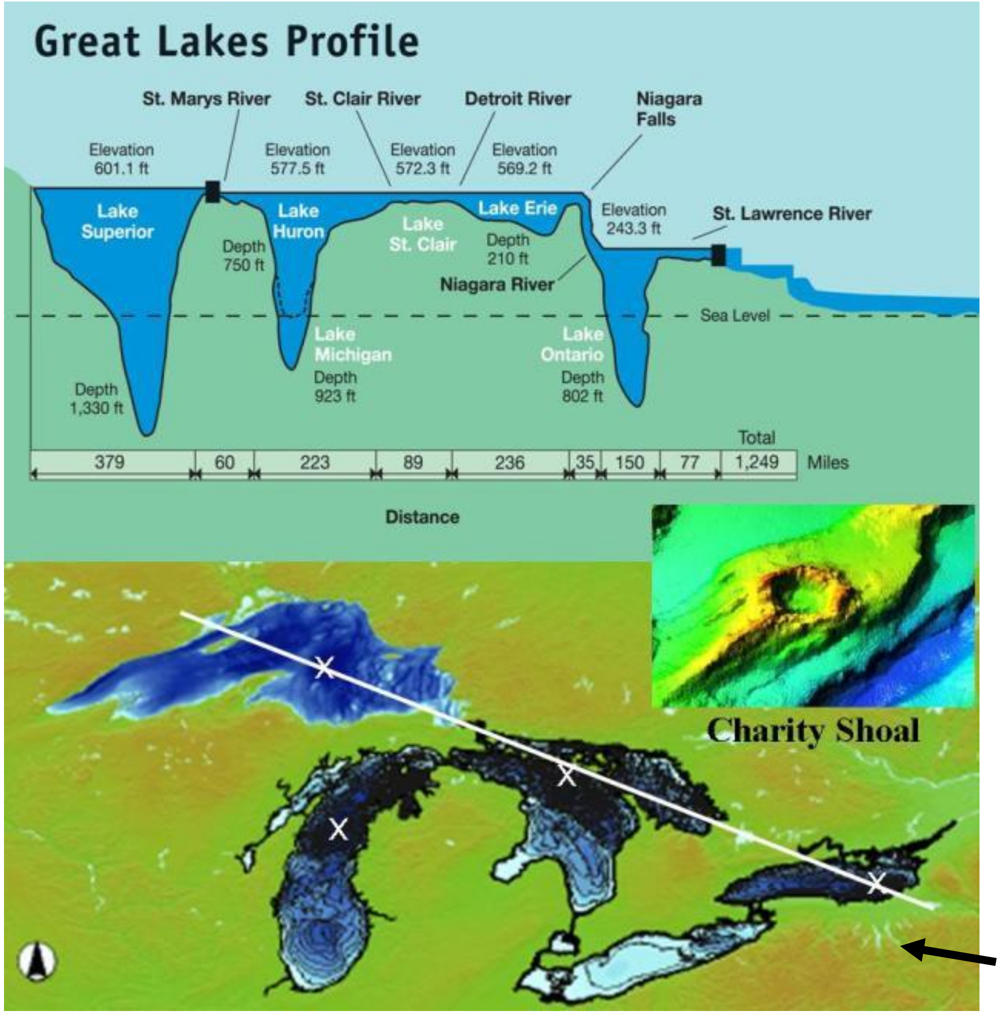
Distribution of impact evidence



- Metallic grains, microspherules, and terrestrial minerals all peak near Gainey, Mi
- Heavy elements including Titanium dominate the ejecta far from Gainey

Conclusion: An impact occurred near the Great Lakes depositing terrestrial debris near the impact site and impactor debris farther away

Are the Great Lakes impact craters?



The basins of four Great Lakes are below sea level.

Lake Superior is the 2nd deepest point on the continental Earth.

Charity Shoal is a 1 km crater or the right age in Lake Ontario

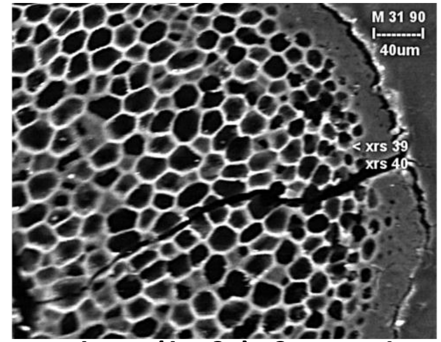
Three of the Great Lakes basins line up like a chain of craters.

The Finger Lakes radiate out from the Lake Ontario basin.

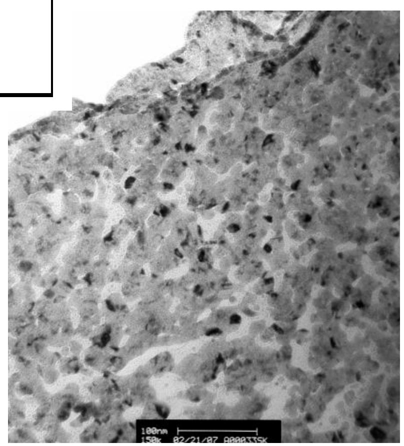
Carbon Spherules

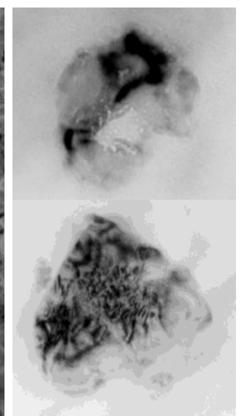
Element	Wt.%/ppm
H_2	5.3%
B	61 ppm
C	82%
N	6.8%
Al_2O_3	2.0%
SiO_2	2.2%
S	0.39%
Cl	0.073%
K_2O	0.12%
CaO	0.5%
TiO_2	0.09%
FeO	0.2%
Cu	0.06%
Cd	0.8 ppm
Sm	0.8 ppm
Gd	0.9 ppm

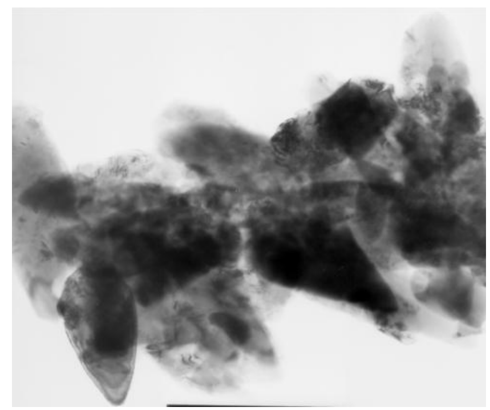
Similar to tree resin $(C_5H_8)_n$ (88%C, 6%H_2)

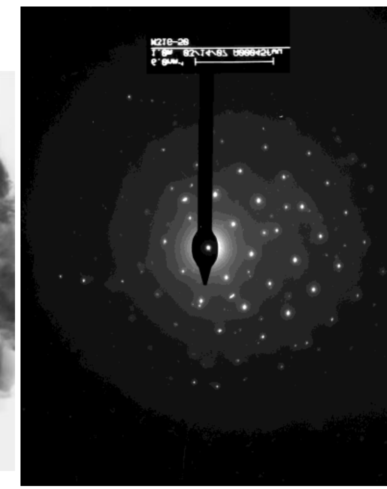


Vesicular carbon microspherules (left) found in the YD boundary layer





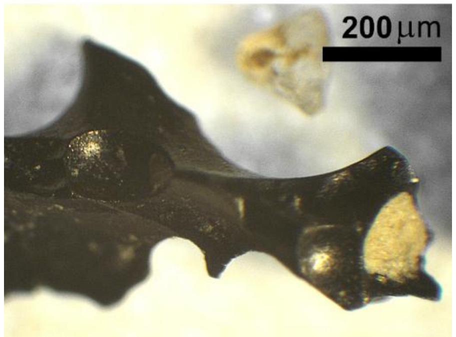




Carbon spherules contain millions of nanodiamonds (<1 μm) often in clusters. XRD shows typical diamond structure. Cubic, hexagonal and n-diamond forms all are found.

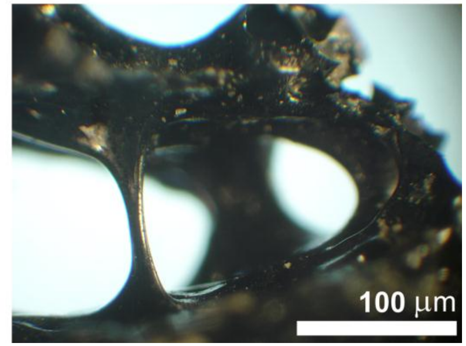
Conclusion: nanodiamonds are only known to be associated with impact events.

Glass-like carbon



Gainey, MI

Murray Springs, AZ



Topper, SC

Glass-like carbon (GLC) also contains nanodiamonds.

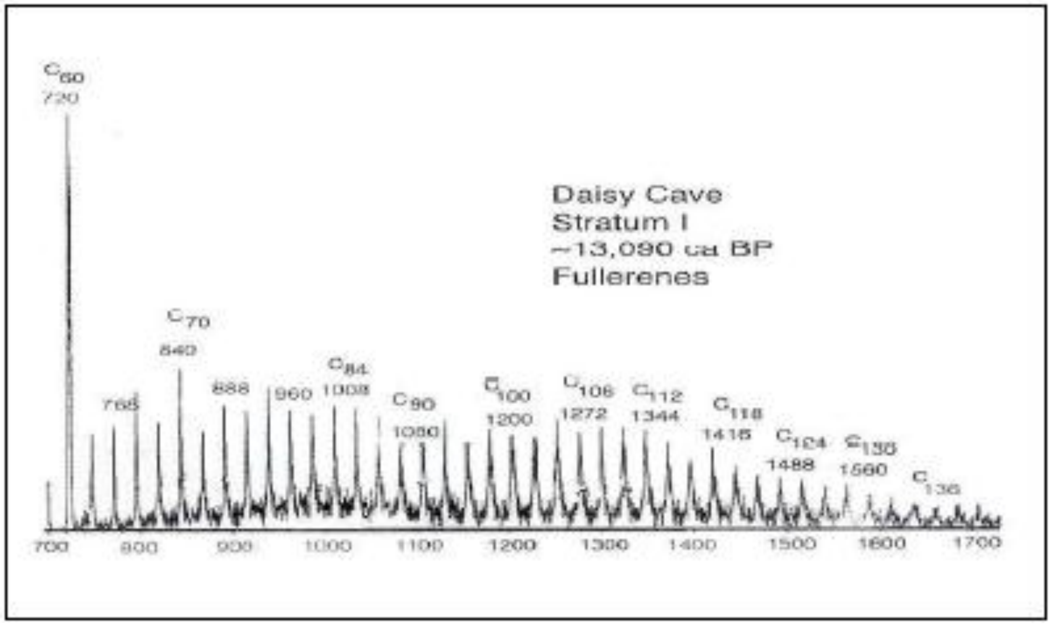
Sample from Carolina Bay grades from GLC at the top to wood (Yellow Pine) at the bottom suggesting that GLC was produced by shockwave heating of trees.

Element	wt.%/ppm
H_2	3.0%
B	10.2 ppm
C	90%
N	0.66%
Al_2O_3	0.97%
SiO_2	4.8%
Cl	181 ppm
K_2O	120 ppm
CaO	0.49%
TiO_2	0.067%
Cd	0.22 ppm
Sm	0.19 ppm
Gd	0.22 ppm

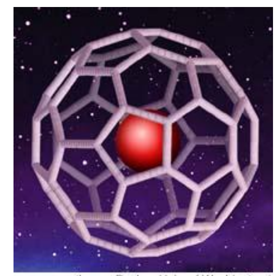
Similar to tree resin $(C_5H_8)_n$

Fullerenes

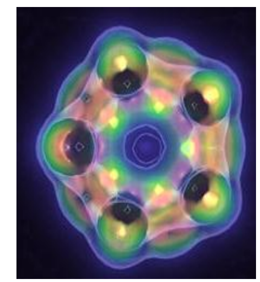
Fullerenes, found in glass-like carbon, were also observed in the KT and PT boundary layers. They contain trapped helium with $^3He/^4He$ ratios greater than 80× terrestrial values.



Laser desorption mass spectrum of fullerenes from Daisy Cave, CA. (Luann Becker, UCSB)

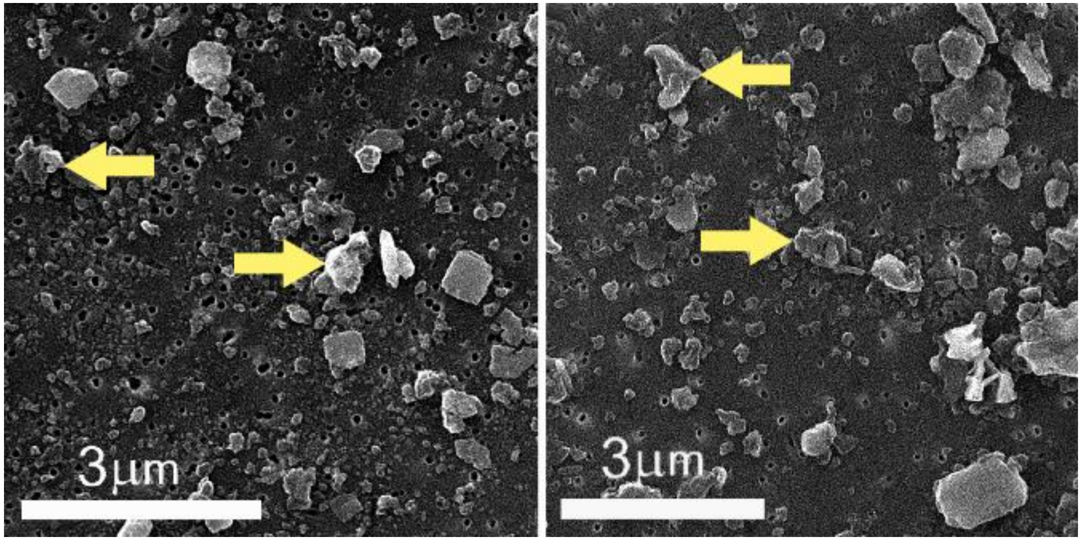


(Luann Becker, Univ. of Washington.)



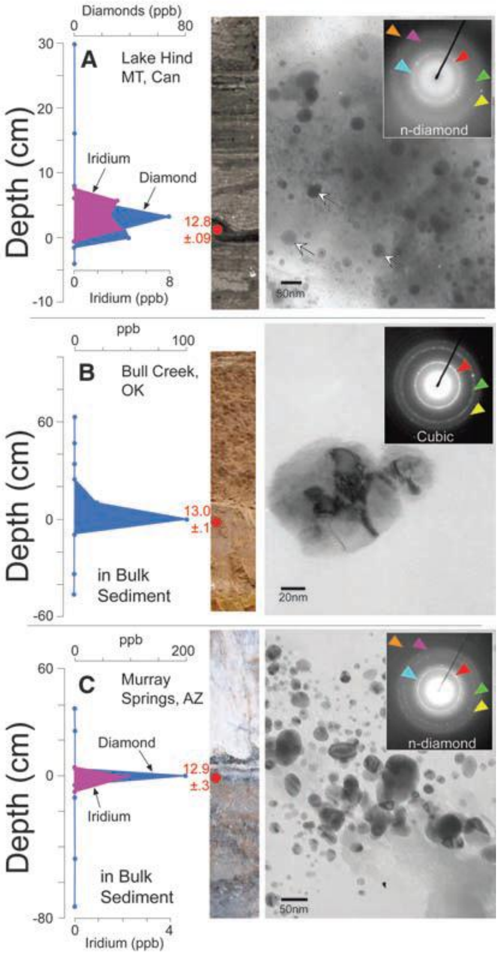
"Buckyball" structure (left) creates a cage suitable for trapping noble gases. SEM image (right) reveals the repeating pentagonal structure.

Soot and Charcoal



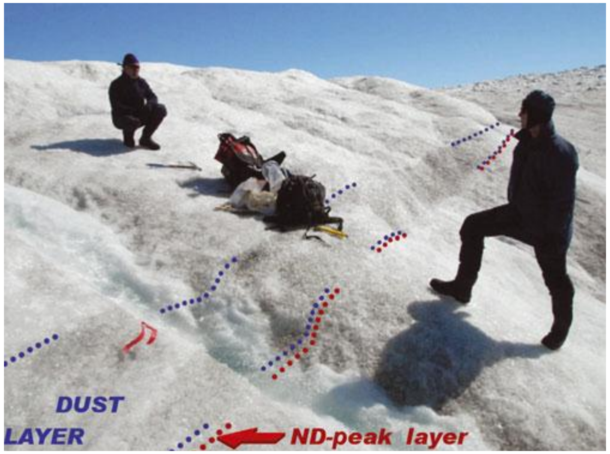
SEM photomicrographs of micron-sized soot (yellow arrows) from a Carolina Bay (left), measured at 1969±167 ppm, and from Murray Springs, AZ (center), measured at 21±7 ppm (Wendy Wolbach, DePaul University). The soot levels and morphology from both sites are similar to those from the K/T. Charcoal (right) was abundant in the YDB. Both soot and charcoal are evidence of extensive fires following the impact.

New Nanodiamond Evidence

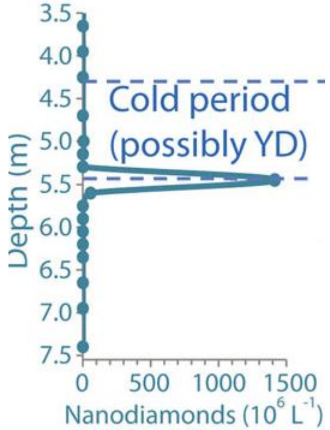


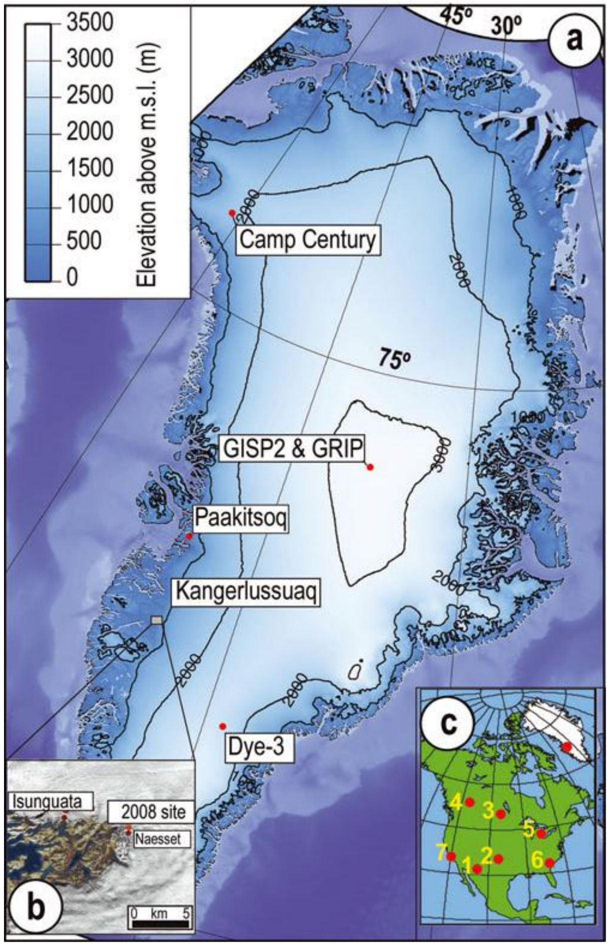
TEM photomicrographs and electron diffraction patterns from several sites

Nanodiamonds have only been found in meteorites. We find them in the impact layer at all sites including Greenland Ice.



Dark ice section dated to time of impact is rich in nanodiamonds.





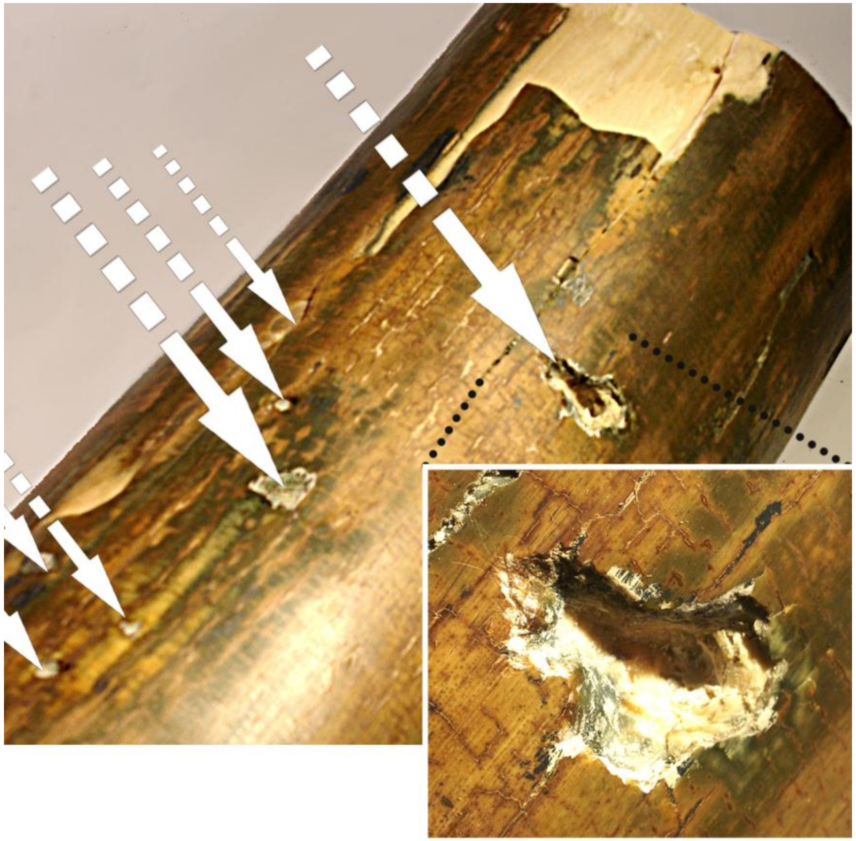
Nanodiamonds found at Kangerlussuaq

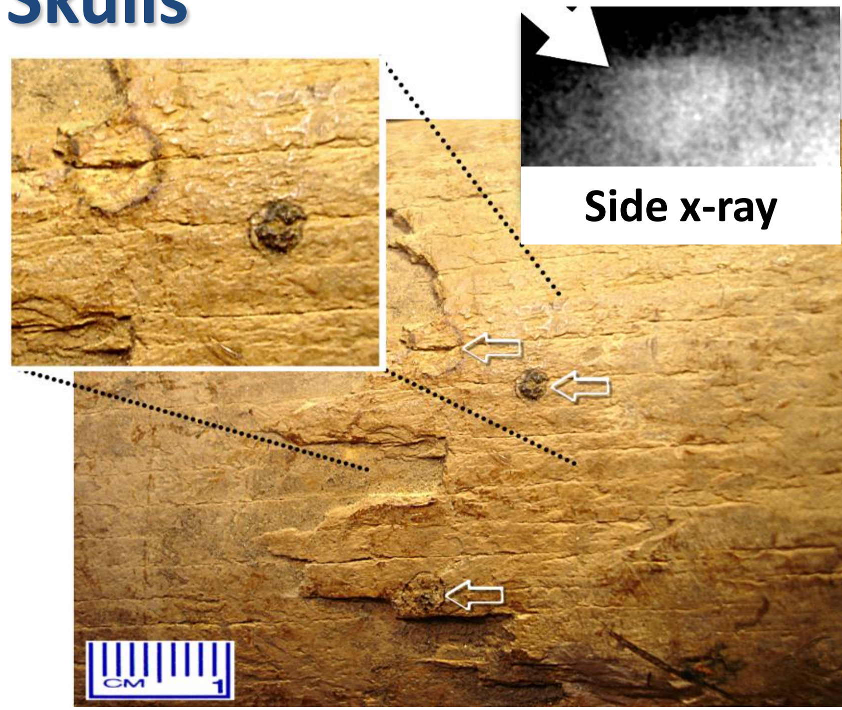
Conclusions

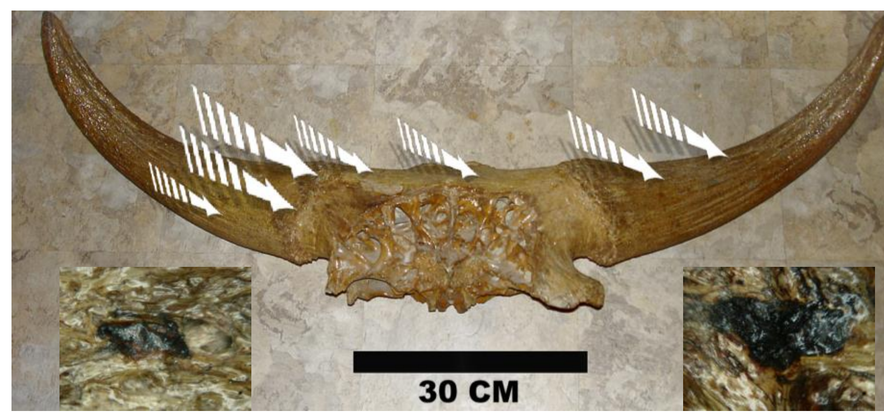
A comet or meteor of unusual Ti-rich, lunar KREEP-like origin struck near the Great Lakes 12,900 years ago causing

1. The extinction of megafauna across North America and beyond
2. Disappearance of the Clovis people
3. Destruction of the Laurentide ice sheet leading to a massive rush of fresh water into the North Sea, interrupting thermohaline circulation and leading to >1000 years of global cooling.
4. Intense high temperature burning of grasslands and forests
5. Deposition of microspherules enriched in Ir and heavy elements
6. Formation of Fullerenes and nanodiamonds
7. Deposition of a black mat formed by algal growth and charcoal deposition
8. Creation of the Carolina Bays from the blast shockwave

Search for micrometeorites in Mammoth Tusks and Bison Skulls







Magnetic particles were found on only one side of mammoth tusks, bison skulls, and musk ox skulls.

Surprising age and composition of the Tusk and Bison Particles

Sample	^{14}C Age
Tusk 05-01	33,000
Tusk 05-01	36,600
Tusk 05-01	35,300
Tusk 05-02A	21,000
Tusk 05-02B	31,800
Tusk 05-02C	31,200
Tusk 05-02D	32,000
Tusk 07-1	34,500
Bison	26,300

Radiocarbon age is
33,500±800 yr!

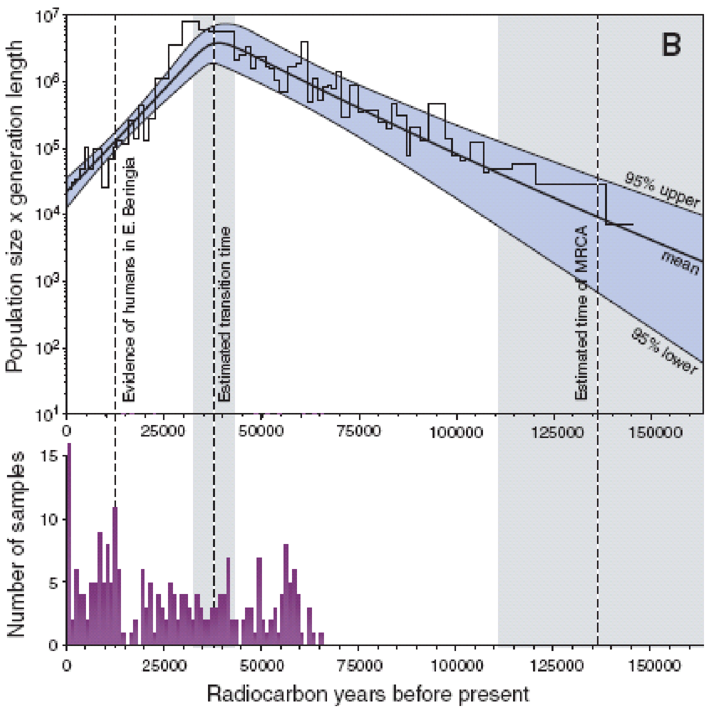
PGAA analysis of the bison particle found 0.36 mg Fe. Consistent with an ~1 mm diameter object.

		Ti/Fe	Mn/Fe	Ni/Fe
Tusk 05-1				
	Sample-1	0.003636	0.018182	0.006818
	Sample-2	0.003676	0.019485	0.005331
	Sample-3	0.004342	0.025439	0.005263
Bison Bi-B				
	Sample-1		0.0019	0.0075
	Sample-2		0.0015	0.0079
Urelite (Novo-Urei)		<0.006	0.02	0.0065
Urelite(Goalpara)		0.0045	0.014	0.0038
CI Chondrite		0.0029	0.012	0.046
Terrestial (crust)		0.13	0.02	0.0009
Black sand		0.0064		<0.0002
LOIB Basalt		0.3	0.017	0.0016
Arc Andesites		0.13	0.02	0.0022

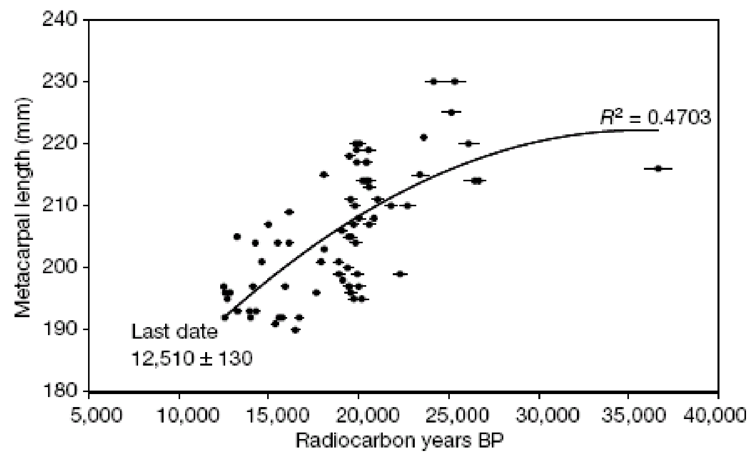
ICP/MS analysis whows that the Tusk and Bison particles are enriched in Ni and depleted in Ti. This composition is clearly meteoritic.

Events in Beringia 34,000 years ago

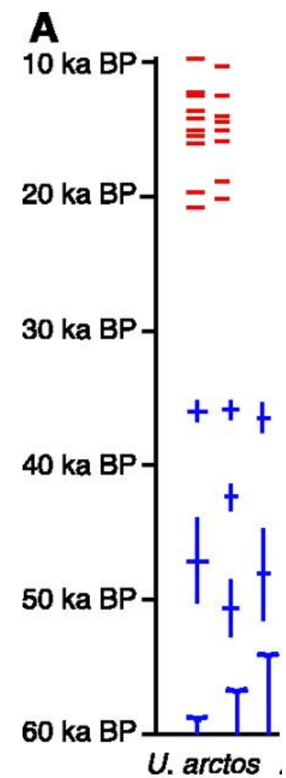
Megafauna populations declined markedly



Decline of Steppe Bison population <36 ka ago. Shapiro *et al*, Science 306, 1561 (2004).



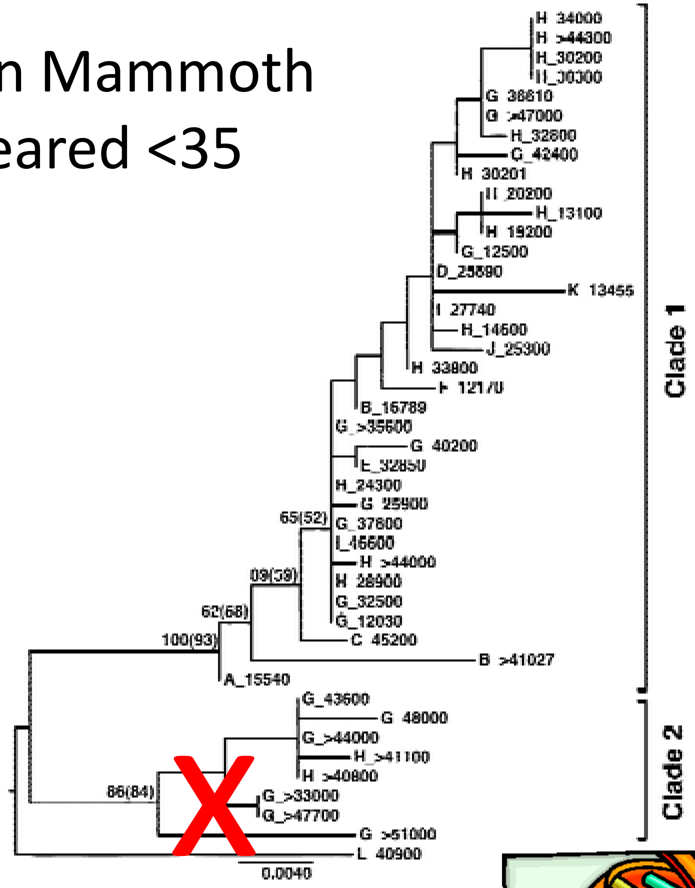
Decline of Alaskan horse population and metacarpal size after 35000 yr BP. (Guthrie, 2003)

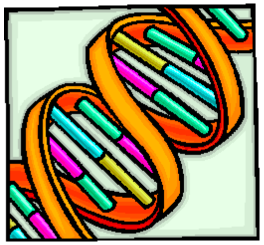


Decline of the brown bear population <35 ka ago
I. Barnes et al, Science 295, 2269 (2002).

Genetic changes <35 kyr ago

One of the two major Beringian Mammoth mitochondrial lineages disappeared <35 kyr ago*.



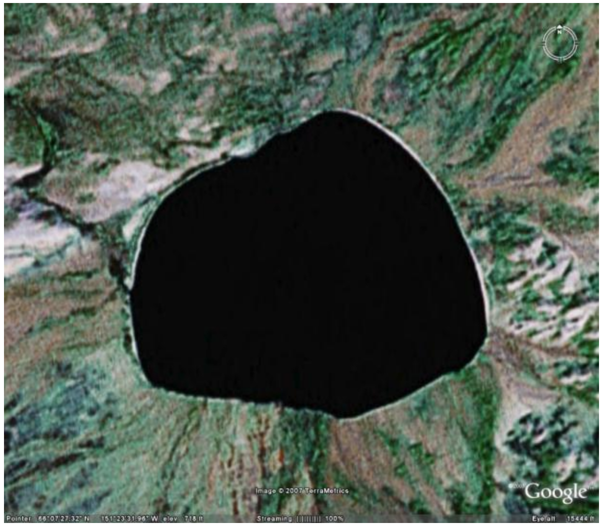


* I. Barnes et al, Current Biology 17, pp 1-4 (2007)

What happened <35 kyr ago?

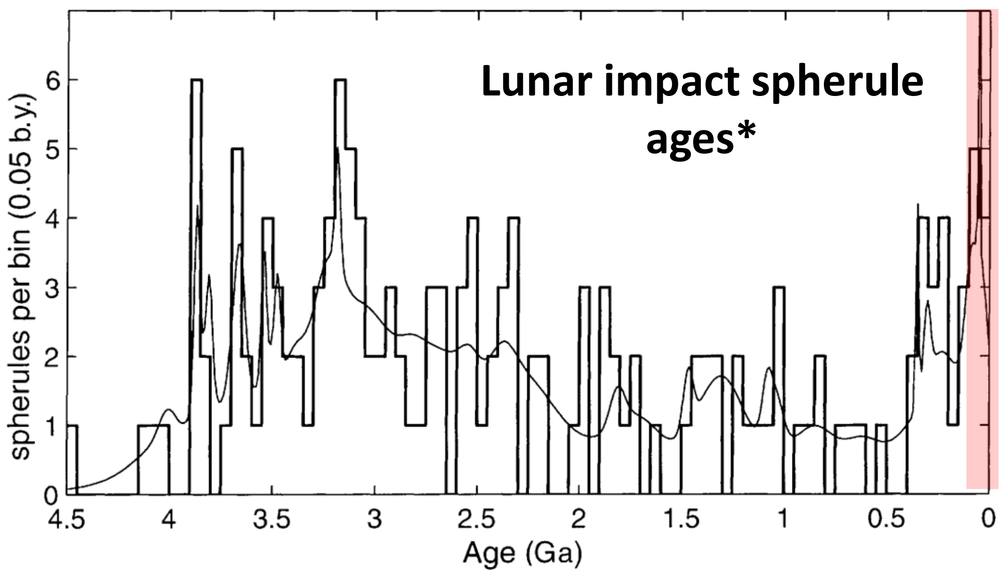
Micrometeorites can't penetrate Earth's atmosphere at high velocity. Possibly a large meteor impacted Beringia shedding micrometeorite shrapnel as it fell.

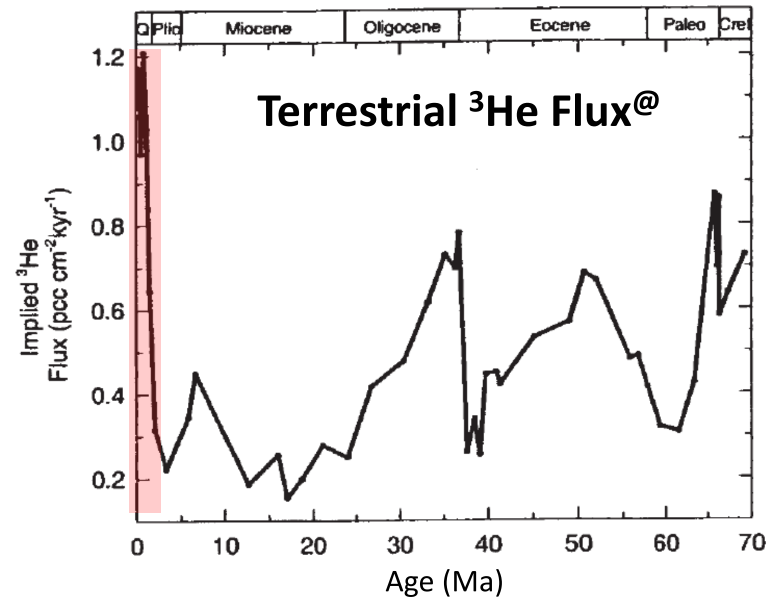
Sithylemenkat Lake (Alaska) may be the impact crater. It is 12 km in diameter and <100,000 years old. Nearby streams contain nickel concentrations of up to 5000 ppm.



Why did this happen so recently. This kind of event is expected to happen once every 10 million years.

Recently the rate of meteorite impacts has increased dramatically





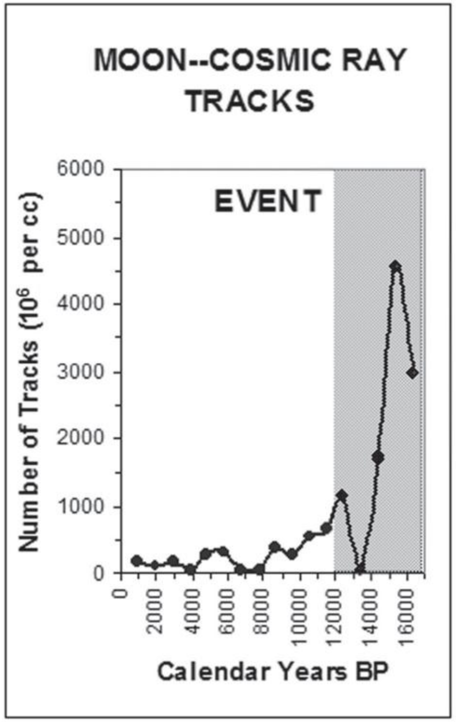
The recent impact rate may have increased by up to an order of magnitude.

Eugene Shoemaker@

* Culler et al, Science **287**, 1785 (2000).

@ Farley (1997) in Shoemaker, J. Royal Astron. Soc. of Canada, **92**, 297 (1998)

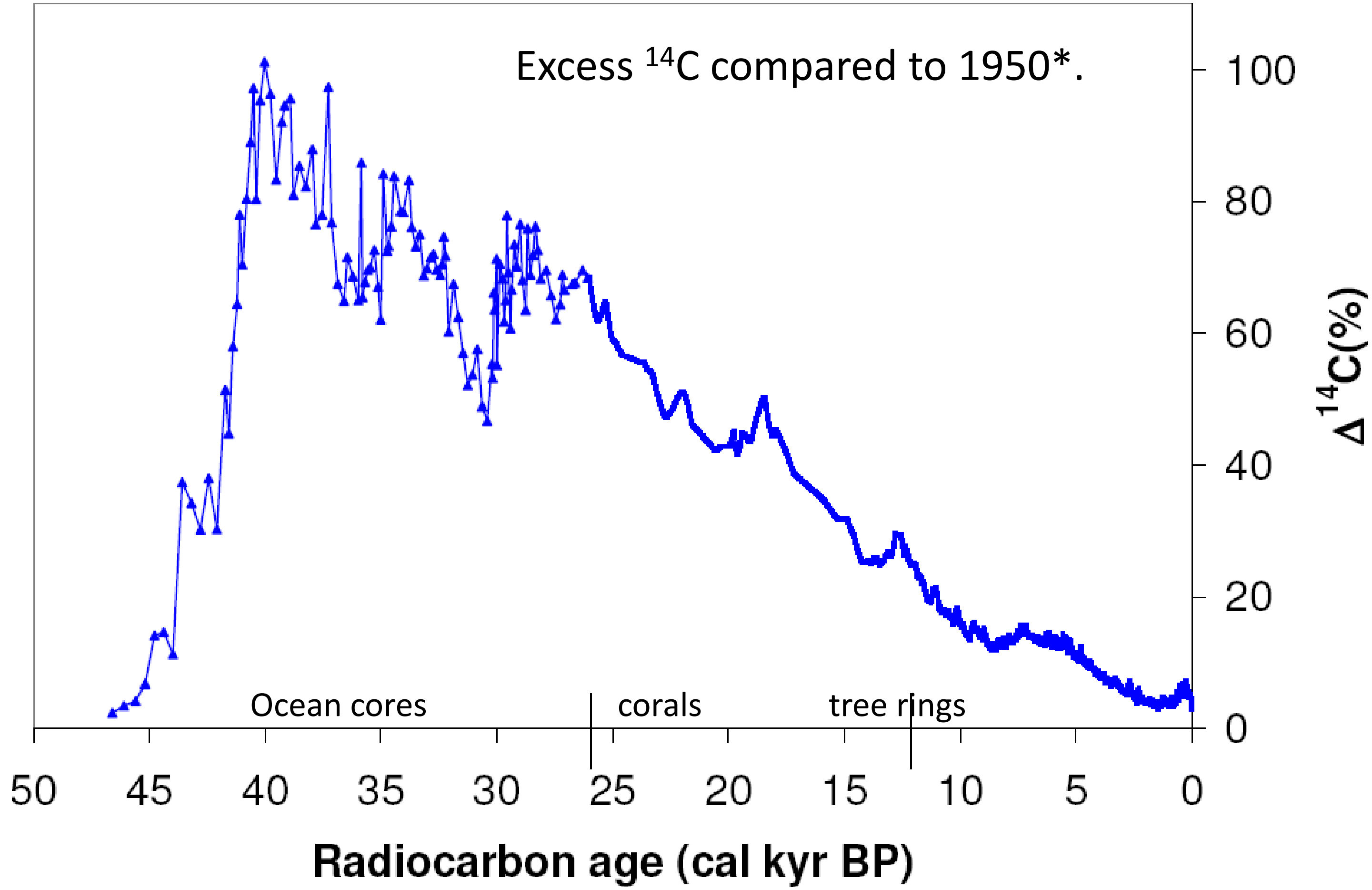
Cosmic ray rates increased on the Moon



Herb Zook (NASA, 1980) suggested that, based on lunar rock cosmic ray track and radioisotope age data, *"a past increase in solar cosmic ray activity"* occurred *"prior to about 20 ka ago".* ^{14}C was 3× the expected value in lunar sediment, confirmed by Tim Jull (1998) who reported that *"over the last 20 ka there cannot have been more than one event >5×10^{13} protons/cm^{2}."*

Lunar Rock	1. Crater Age	2. Track Age	3. ^{26}Alum. Age	Ratio of #2/#1	More Past Radiation
12054	26,500	175,000	~150,000	6.6	**Yes**
15205	15,300	80,000	~100,000	5.2	**Yes**
60015	20,000	150,000	---	7.5	**Yes**

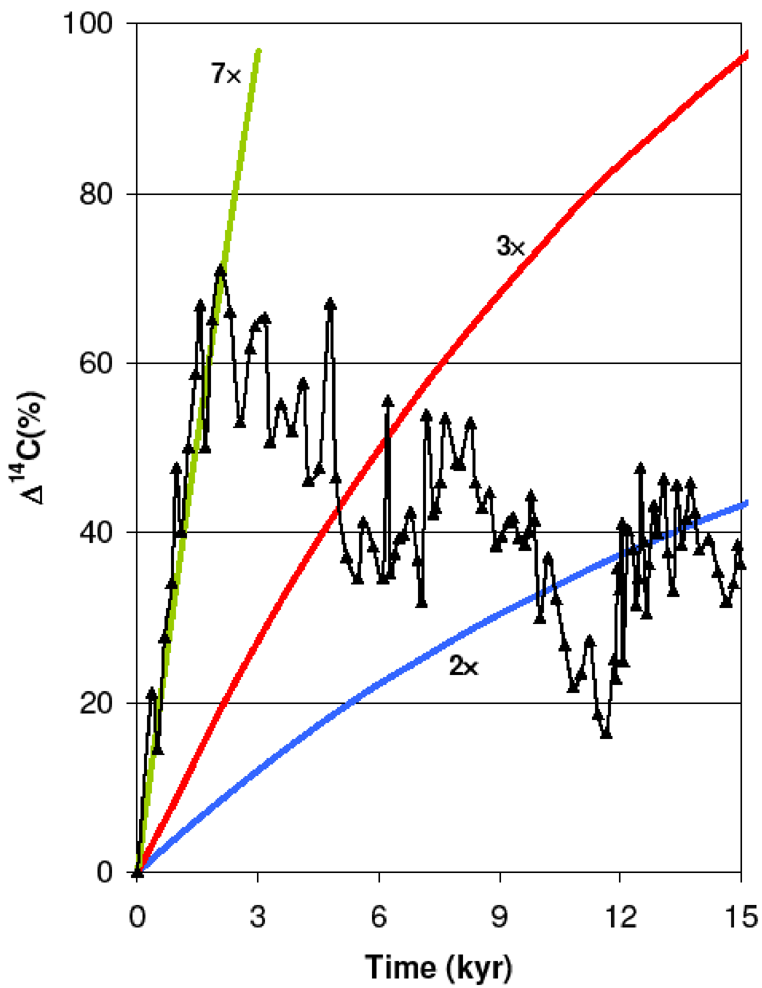
Radiocarbon cosmic ray evidence



44-40 kyr ago global radiocarbon suddenly doubled.

* **Reimer et al, INTCAL04,** Radiocarbon **46**, 1029–1058 (2004)

Could the disappearance of Earth's magnetic field explain the ^{14}C increase?

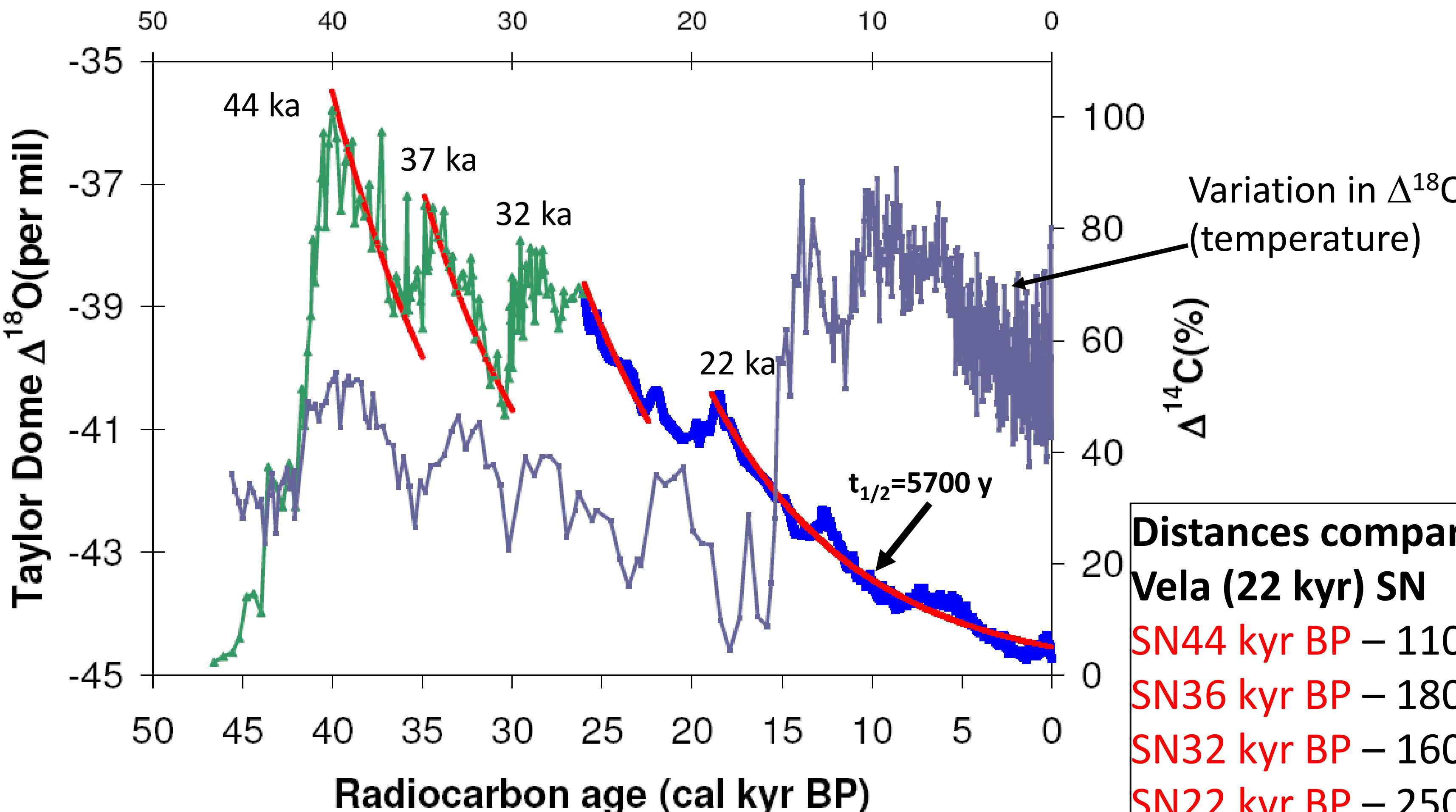


Reimer et al proposed this increase was due to a 2-3× increase in the rate of ^{14}C production predicted if Earth's magnetic field disappeared.

- Requires 23 kyr to double ^{14}C pool
- 7× increase is needed to explain the data

The ^{14}C increase cannot be explained by magnetic field changes

Supernova origin of ^{14}C increase

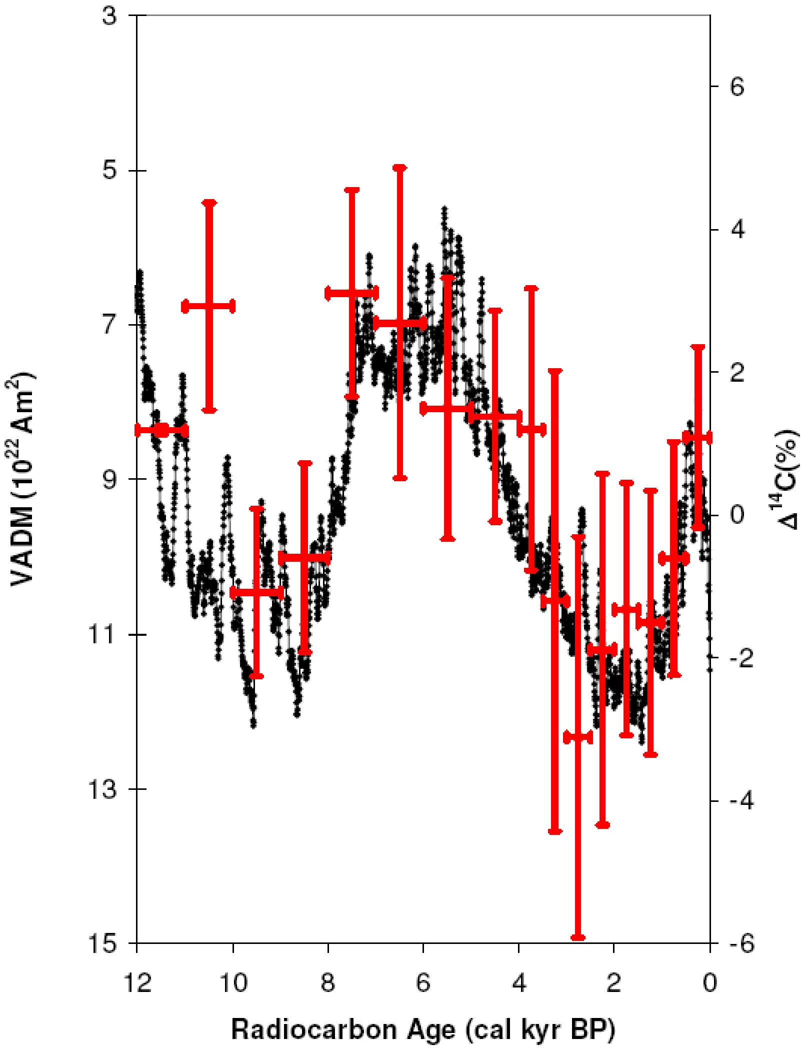


Distances compared to Vela (22 kyr) SN

SN44 kyr BP – 110 pc
SN36 kyr BP – 180 pc
SN32 kyr BP – 160 pc
SN22 kyr BP – 250 pc

Global radiocarbon produced by each supernova decays (red curve) with the ^{14}C half-life.

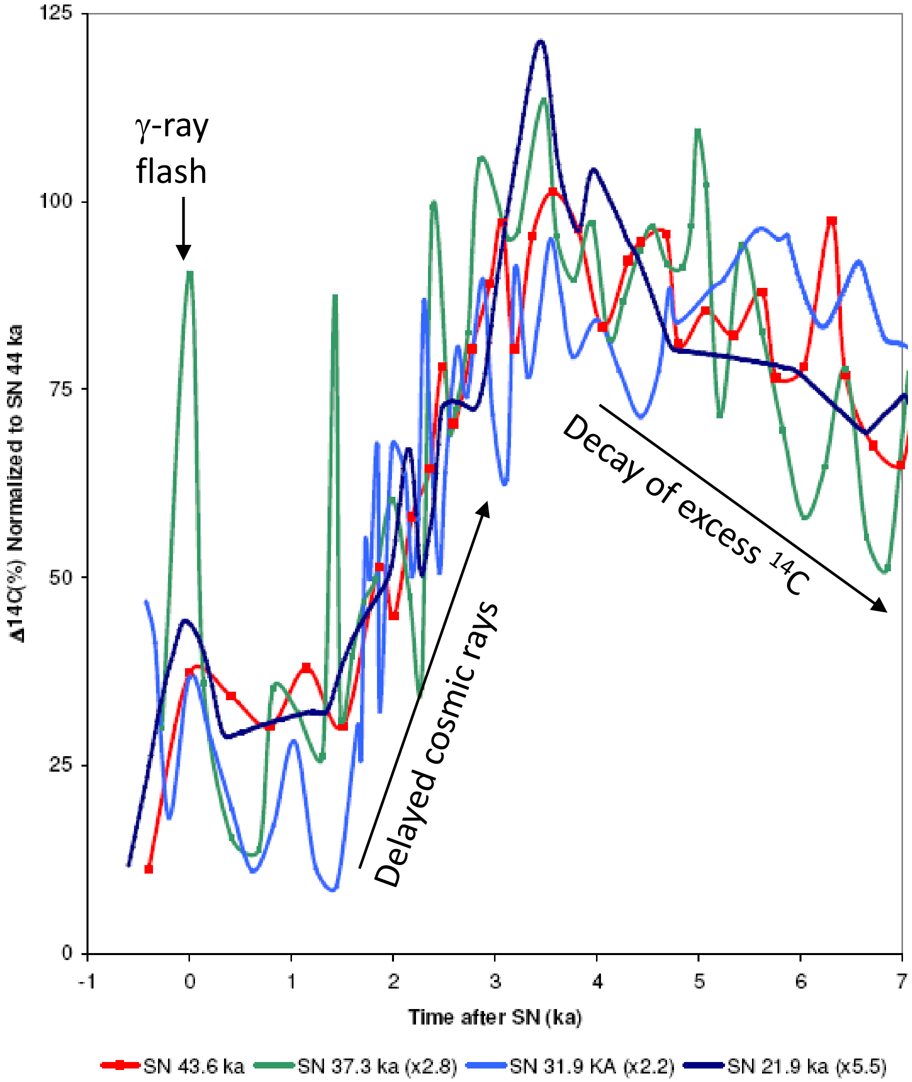
Earth's Magnetic Field Affects



Difference between experimental $\Delta^{14}C$ and expected $\Delta^{14}C$ from the decay curve.

Experimental fluctuations in $\Delta^{14}C$, due to variations in the Earth's magnetic field (black) are comparred to variations in Earth's magnetic field (red).

The Supernova Signature



Renormalizing ^{14}C to a common scale for each supernova we find the expected signature

- Sudden increase in ^{14}C due to γ-rays and neutrinos
- Steady increase in ^{14}C due to cosmic rays for centuries.
- Decay of excess ^{14}C with 5700 y half-life

Measurement: $E_{CR} = 3\times10^{50}$ ergs

Earth's Recent Neighborhood

We live in the outskirts of the Milky Way where giant stars are born only to die soon in fiery supernovae

It is estimated that about 20 supernovae exploded near Earth in the past 10 Myr.

This may have stirred up the solar system causing an increas in impacts.

We live in the middle of a local bubble formed by the debris of nearby supernovae.

Radiocarbon: The Last Frontier?

Radiocarbon age of various samples from the 12,900 year old YDB layer.

UCI-AMS#	YDB Site	Sample Depth (cm)	Date (yr)
	Carbon spherules		
29311	Blackville Bay	30	-755 ± 15
29302	Sewell Bay	110	-400 ± 15
29305	Bladen Bay	80	-180 ± 20
29316	Gainey	20	-135 ± 15
29297	Myrtle Bay	97	275 ± 20
	Woody debris		
29327	Myrtle Bay	163	-685 ± 15
29328	Myrtle Bay	173	305 ± 20
	Glass-like carbon		
29318	Myrtle Bay 2	70	685 ± 15
29309	Bladen Bay	173	2630 ± 20
29301	Sewell Bay	20	4230 ± 15
29308	Bladen Bay	122	5820 ± 15
29299	Myrtle Bay	97	6395 ± 25
29304	Bladen Bay	15	8455 ± 20
	Charcoal		
29313	Blackville Bay	145	-510 ± 15
29312	Blackville Bay	145	35 ± 15
29300	Myrtle Bay	127	1265 ± 20
29314	Chobot Clovis	12	1520 ± 20
29303	Sewell Bay	130	2990 ± 15
29315	Chobot Clovis	15	3645 ± 20
29298	Myrtle Bay	97	4760 ± 20
29306	Bladen Bay	106	6540 ± 15
29307	Bladen Bay	122	6565 ± 15

Summary of all radiocarbon ages of Clovis Paleo-Indian sites

Clovis site	Date(yr)	Date (yr)
Sandy Ridge, ON	735 ± 65	735±65
Leavitt, MI-1	1100 ± 600	1100±600
Leavitt, MI-2	7886 ± 116	7886±116
Alton, IN	1860 ±	1860
Thedford, ON	2130 ± 230	2130±230
Gainey, MI	2830 ± 175	2830±175
Zander, ON	3380 ± 420	3380±420
Potts, NY	3810 ±	3810
CB-North IL-1	3190 ± 330	3190±330
CB-North IL-2	4000 ± 90	4000±90
CB-North, IL-3	4180 ± 40	4180±40
Halstead, ON	6030 ± 60	6030±60
Sheridan Cave, OH		≥12640
Paleo Crossing, OH		12900±200

Radiocarbon ages of carbon from the YDB impact are too young

- ^{14}C produced by D+D fusion reactions in flight or on impact
- ^{14}C produced in recent (<40 kyr) supernova

Thank you for your attention

Further reading:

1. **Younger Dryas Impact Event (12,900 yr BP)**
   a. *Cycle of Cosmic Catastrophes*, R.B. Firestone, A. West, Inner Traditions (2007)
   b. R.B. Firestone et al, *Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling,* PNAS 104, 16016 (2007). (101 citations since publication)
   c. R.B. Firestone, *The Case for the Younger Dryas Extraterrestrial Impact Event: Mammoth, Megafauna and Clovis Extinction,* Journal of Cosmology 2, 286-288 (2009).
   d. R.B. Firestone, et al, *Analysis of the Younger Dryas Impact Layer,* J. Siberian Federal University. Engineering and Technologies 1, 30-62 (2010).
2. **Meteorite Impacts in Mammoth Tusks (35,000 yr BP)**
   a. R.B. Firestone, *Evidence of four prehistoric supernovae <250 pc from Earth during the past 50,000 years,* American Geophysical Union Fall Meeting, 14-18 December 2009, San Francisco, CA, paper PP31D-1386.
   b. *Micrometeorite Impacts in Beringian Mammoth Tusks and a Bison Skull,* J.T. Hagstrum, R.B. Firestone2, A. West, Z. Stefanka, Z. Revay, J. Siberian Federal University. Engineering and Tecjnologies 1, 123-132 (2010).
3. **Discovery of Near-Earth Prehistoric Supernovae 44-, 37-, 32-, and 22-kyr ago**

   R.B. Firestone, *Evidence of Four Prehistoric Supernovae ≤250 pc from Earth during the Past 50,000 Years,* American Geophysical Union Fall Meeting, 14-18 December 2009, San Francisco, CA, paper PP31D-1386. - LBNL-79199