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The Case for the Younger Dryas Extraterrestrial Impact Event:

Mammoth, Megafauna, and Clovis Extinction, 12,900 Years Ago.

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Abstract

The onset of >1000 years of Younger Dryas cooling, broad-scale extinctions, and the disappearance of the Clovis culture in North America simultaneously occurred 12,900 years ago followed immediately by the appearance of a carbon-rich black layer at many locations. *In situ* bones of extinct megafauna and Clovis tools occur only beneath this black layer and not within or above it. At the base of the black mat at 9 Clovis-age sites in North America and a site in Belgium numerous extraterrestrial impact markers were found including magnetic grains highly enriched in iridium, magnetic microspherules, vesicular carbon spherules enriched in cubic, hexagonal, and n-type nanodiamonds, glass-like carbon containing Fullerenes and nanodiamonds, charcoal, soot, and polycyclic aromatic hydrocarbons. The same impact markers were found mixed throughout the sediments of 15 Carolina Bays, elliptical depressions along the Atlantic coast, whose parallel major axes point towards either the Great Lakes or Hudson Bay. The magnetic grains and spherules have an unusual Fe/Ti composition similar to lunar Procellarum KREEP Terrane and the organic constituents are enriched in ^{14}C leading to radiocarbon dates often well into the future. These characteristics are inconsistent with known meteorites and suggest that the impact was by a previous unobserved, possibly extrasolar body. The concentration of impact markers peaks near the Great Lakes and their unusually high water content suggests that a 4.6 km-wide comet fragmented and exploded over the Laurentide Ice Sheet creating numerous craters that now persist at the bottom of the Great Lakes. The coincidence of this impact, the onset of Younger Dryas cooling, extinction of the megafauna, and the appearance of a black mat strongly suggests that all these events are directly related. These results have unleashed an avalanche of controversy which I will address in this paper.

Keywords: Younger Dryas, Extinctions, Extraterrestrial Impacts, Black Mat, Clovis, Mammoth, Megafauna

1. Introduction

Approximately 12.9 ka ago the Northern Hemisphere suddenly experienced a return to glacial conditions lasting >1000 years called the Younger Dryas (YD) that reversed the warming of the preceding interstadial deglaciation (Alley, 2000). A common explanation for this cooling is the shutdown of the North Atlantic thermohaline circulation following a sudden influx of fresh water from the deglaciation of North America (Broecker, 2006). The impetus for this shutdown and the rapid deglaciation of North America has been a mystery. At the same time mammoths, many other megafauna, smaller mammals, and birds suddenly became extinct in North America. At least 35 mammal genera disappeared (Grayson and Meltzer, 2003) and all evidence of Clovis culture in North America abruptly ended (Waters and Stafford, 2007).

C. Vance Haynes (2008) has identified a black, organic-rich layer or "black mat" at 70 Clovis-age sites that started forming 12.9 ka ago (Taylor et al. 1996). As Haynes described it, the "mat covers the Clovis-age landscape on which the last remnants of the terminal Pleistocene megafauna are recorded." No skeletal remains of horse, camel, mammoth, mastodon, dire wolf, American lion, short-faced bear, sloth, tapir, etc., or Clovis artifacts have ever been found *in situ* within or stratigraphically above the YD-age black mat. Haynes (2006) concluded that the "extinction of the Rancholabrean megafauna was geologically instantaneous, essentially catastrophic." This is inconsistent with other theories proposed to explain their disappearance including human overkill (Mosimann and Martin, 1975). Human predation fails to explain either the absence of kill sites for 33 extinct mammals or the rapidity with which they disappeared.

Abrupt Younger Dryas cooling has also been implicated in the demise of these megafauna and mammals (Guthrie, 2006). However, similar episodes have often occurred during the past 80 ka, and none were associated with major extinctions. Additionally, no evidence exists for suspected pandemic disease (MacPhee and Marx, 1997) in the Pleistocene record, and the elimination of so many varied species by disease seems unlikely.

Simultaneous sudden extinctions and rapid onset of Younger Dryas cooling, followed by the appearance of the black mat, clearly indicate that a catastrophic event such as major volcanism or an extraterrestrial impact event occurred 12.9 ka ago. However, analysis of sulfate in Greenland ice (Zielinski et al. 1996) indicates that there was no major North American volcanic episode sufficient to have caused a catastrophe of this magnitude at that time.

Consistent with an extraterrestrial impact event, Firestone et al. (2007) reported the discovery of a thin sediment layer at the base of the black mat at 10 Clovis-age sites across North America and a site in Belgium containing numerous markers indicative of impact. Extensive stratigraphic and chemical analysis of sediments from these sites shows that this impact was capable of causing the Laurentide Ice Sheet to fail and the catastrophic conditions leading to the megafaunal extinctions. The black mat then would have formed from the ashes of the impact and the decay of plant and animal debris.

2. Evidence of a Younger Dryas Impact Event

In the 1990's William Topping investigated the Gainey, MI Clovis site where he found, within the artifact layer, a large abundance of magnetic grains and spherules, elevated radioactivity, and cosmic ray tracks in chert flakes which he attributed to an extraterrestrial event (Firestone and Topping, 2001). These results were unverified until 2004 when Allen West investigated the Clovis-age kill site at Murray Springs, AZ where the black mat is especially clearly visible and well defined. There he found megafaunal remains, mammoth tracks, and Clovis artifacts, all of which were in direct contact with the black mat. Armed only with a strong magnet and a Geiger counter, West found that the upper surfaces of mammoth fossils, which were directly covered by the black mat, were strongly magnetic and radioactive. No magnetism or excess radioactivity was found on the lower surfaces of these same fossils where they had extended below the black mat.

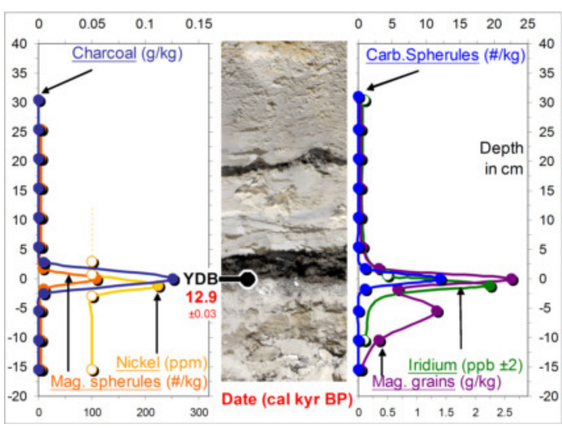

Figure 1. Sediment profile for Murray Springs indicating that magnetic grains, microspherules, carbon spherules, charcoal, iridium, and nickel all peak at the base of the black mat. Sampling intervals of 0.6 cm were necessary to see the YDB layer. Similar results were obtained at 8 other Clovis-age sites in North America and a Usselo site in Lommel Belgium.

Similar magnetism and radioactivity was observed at the base of the black mat at Murray Springs where magnetic grains could be pulled out of the hillside with a magnet. West, using microstratigraphy, collected sediment samples from above, below, and at the base of the black mat, and samples near a narrow 2-3 mm layer directly beneath the black mat where the magnetic grains and radioactivity were most intense. In this narrow layer West identified high concentrations of magnetic grains and spherules, charcoal, soot, polycyclic aromatic hydrocarbons (PAHS), Fullerenes, and glass-like carbon. The distribution of these YDB layer markers at Murray Springs is shown in Fig. 1. No magnetic spherules, carbon spherules, Fullerenes, soot or PAHS were observed either above or below this narrow layer. These markers are evidence of an extraterrestrial impact event and the high-temperature grass and forest fires that followed.

West went on to investigate sediment profiles around the Younger Dryas boundary (YDB) layer at eight additional Clovis-age sites in North America. These includes sediment samples from a Clovis-age site in Lommel Belgium provided by Han Kloosterman. At each site the same markers peaked in the YDB, and at many sites an additional marker, an abundance of vesicular carbon spherules later found to contain cubic and n-type nanondiamonds. Examples of the magnetic spherules, carbon spherules, and glass-like carbon are shown in Fig. 2. A summary of the markers found at the YDB research sites is given in Table 1.

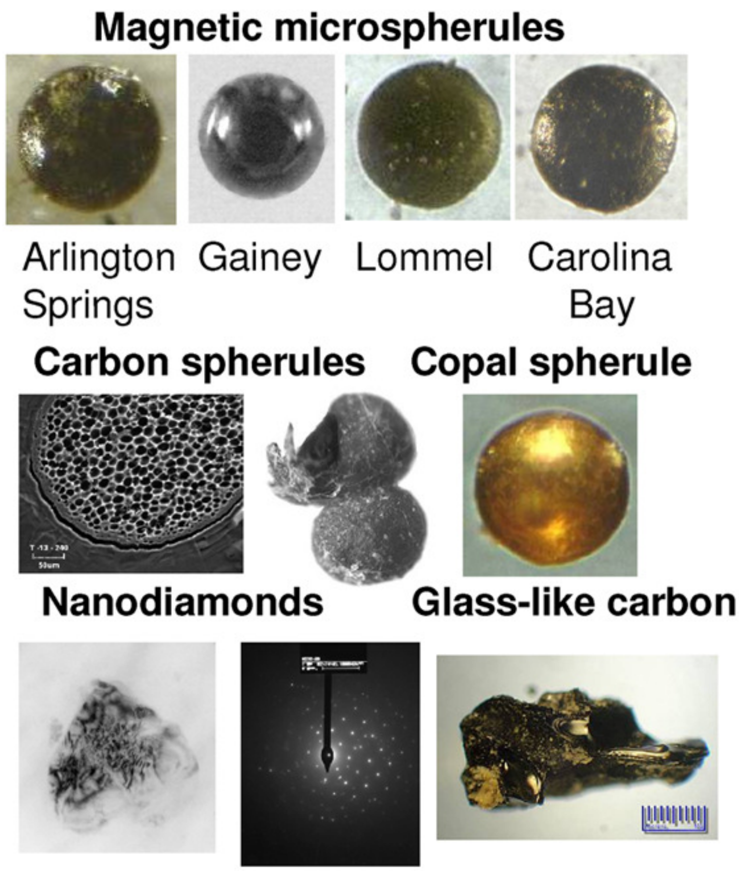

Figure 2. Examples of impact markers found at various Clovis-age sites in the YDB layer. Magnetic spherules ranged from 20-100 µm in diameter. Vesicular carbon spherules, up to 3 mm in diameter, were found at most sites and separated from sediment samples by flotation. They were often found together with copal spherules. Nanodiamonds were found at high abundance inside carbon spherules and identified by XRD analysis. Glass-like carbon, found at many sites, is shiny with an appearance of having been melted.

Table 1. Summary of YDB Research Sites and Concentration of Selected YDB Markers

		Magnetic Grains					Microspherules			Carbon	
Clovis-age YDB Sites	Date ka	Total g/kg	Ir ppb	H_2O %	FeO %	TiO_2 %	Spher. #/kg	FeO %	TiO_2 %	Spher. #/kg	Other markers
Gainey, MI	≈12.4	3.2	<2	3.2	14	1.6	2144	41	25	1232	agc
Murray Springs, AZ	12.99	2.6	<1	5.1	21	16	109			0	akgcfpsb
Blackwater Draw, NM	12.98	2.1	24	1.5	27	8.1	768	56	33	0	akgcfpb
Chobot, AB	≈13	1.9		5	14	0.9	578			11	ahcb
Wally's Beach AB	12.97	7.8	51	1.6	41	8.3	6			0	ak
Topper, SC	<13.5	1.1	2	0.7	25	49	97			2	agc
Lommel, Belgium	12.94	0.8	117	0.8	23	21	16	14	67	0	acb
Morley Drumlin, AB	≈13	9.9	<0.1	3.7	14	1.4	1020	60	27	16	gcb
Daisy Cave/Arlington Springs, CA	13.09	>0					>0			>0	gcfpb
Lake Hind, MB	12.76	0.3					0			184	gcb
Carolina Bays (min)		0.5	<1	0.3	18	21	20			142	gcfs
Carolina Bays (max)		17	15	1.3	26	34	205			1458	

Radiocarbon ages are calibrated. Percentages are by weight. Other markers: **a**-Clovis artifacts, **k**-megafaunal kill site, **g**-glass-like carbon, **c**-charcoal, **f**-Fullerenes, **s**-soot, p-polycyclic aromatic hydrocarbons, **b**-black mat.

West also investigated sediment from 15 Carolina Bays, elliptical depressions found along the Atlantic coast from New England to Florida (Eyton and Parkhurst, 1975), whose parallel major axes point towards either the Great Lakes or Hudson Bay as seen in Fig. 3. Similar bays have tentatively been identified in Texas, New Mexico, Kansas, and Nebraska (Kuzilla, 1988) although they are far less common in this region. Their major axes also point towards the Great Lakes. The formation of the Carolina Bays was originally ascribed to meteor impacts (Melton and Schriever, 1933) but when no meteorites were found they were variously ascribed to marine, eolian, or other terrestrial processes.

West found abundant microspherules, carbon spherules, glass-like carbon, charcoal, Fullerenes, and soot throughout the Carolina Bays but not beneath them as shown in Fig. 4. Outside of the Bays these markers were only found only in the YDB layer as in other Clovis-age sites.

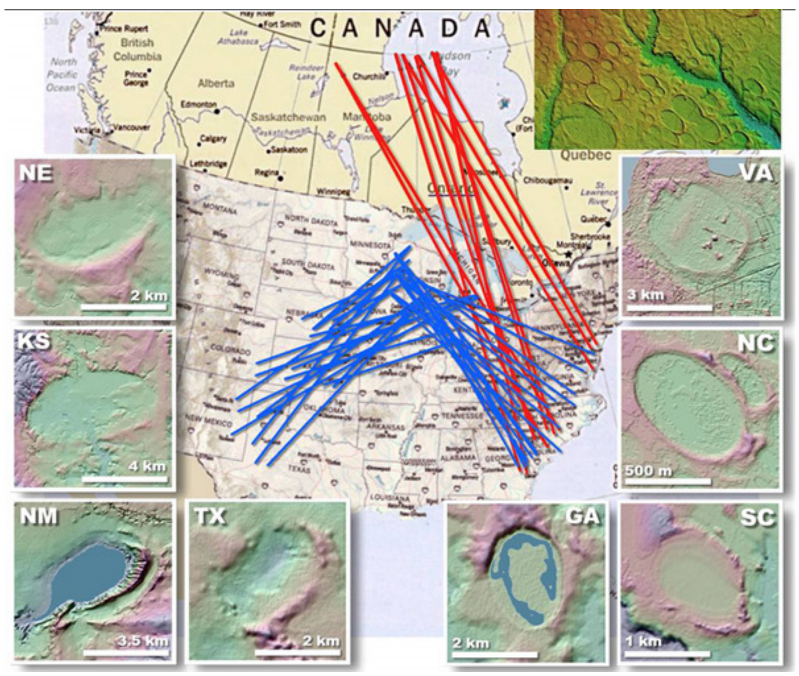

Figure 3. The Carolina Bays are »500,000 elliptical, shallow lakes, wetlands, and depressions, up to »10 km long, with parallel major axes (see inset) pointing toward the Great Lakes or Hudson Bay. Similar features found in fewer numbers in the plains states also point towards the Great Lakes. These bays were not apparent topographical features until the advent of aerial photography.

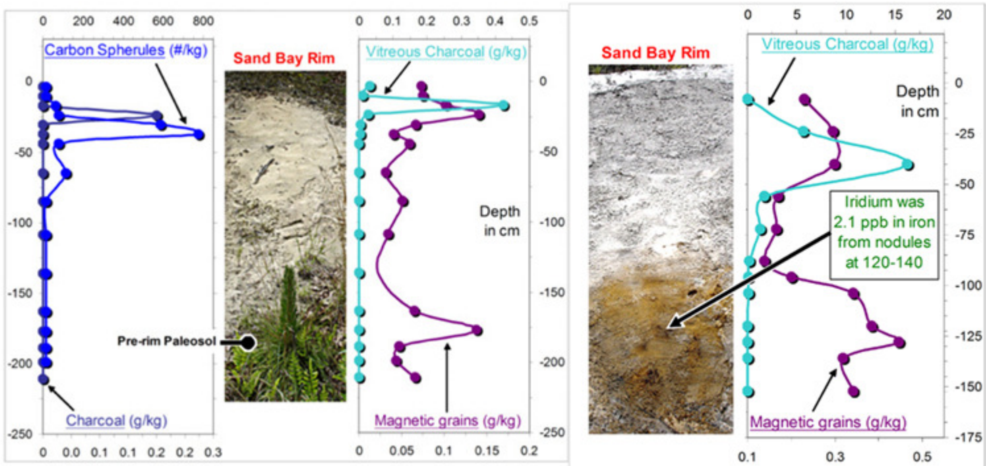

Figure 4. At two sandy Carolina Bays magnetic grains, carbon spherules and glass-like carbon (vitreous charcoal) are found distributed throughout the Bay sediment.

3. Chemistry of the Magnetic Grain and Microspherules

As discussed in detail by Firestone et al (2008) magnetic grains and sediments were analyzed with Neutron Activation Analysis (NAA) at Becquerel Laboratories and Activation Laboratories in Canada to determine trace element concentrations. Prompt Gamma-ray Activation Analysis (PGAA) (Perry, 2001) is sensitive to all elements from hydrogen to uranium and was used at the Budapest Neutron Center to determine the primary elemental composition of the samples. Microspherules were analyzed by SEM/XRF at Cannon Microprobe, Seattle and at the USGS, Menlo Park. The abundance of ^{40}K was analyzed at the Lawrence Berkeley Laboratory's Low-Background g-ray Counting Facility (see Firestone et al 2008, for additional details).

Iridium: Ir is very rare in the Earth's crust but is highly concentrated at the core. It commonly is found in a high abundance in meteorites and is a well known marker for the K/T impact layer (Alvarez et al. 1980). We analyzed for Ir in magnetic grains and sediments from strata above, below, and within the YDB and the Carolina Bays by NAA (Table 1). For YDB magnetic grains from 7 of 12 sites Ir values ranged from of 2(±90%) to 117(±10%) ppb. The highest Ir abundance in magnetic grains is »25% that of typical chondrites (455-480 ppb) (McDonough and Sun, 1995) and >5000°— crustal abundance (0.021 ppb) (Rudnick and Gao, 2003). In 17 samples of magnetic grains taken from above or below the YDB no Ir was detected. Magnetic grain sample sizes were small and Ir fluctuations can be ascribed to the varying background of naturally occurring magnetite and the "nugget effect" due to small sample sizes. For bulk sediment samples, YDB Ir ranged of 0.5(±90%) to 3.75(±50%) ppb and no Ir was found above or below the YDB in 45 bulk sediment samples. Since the YDB layer is very thin, bulk samples contained substantial quantities of terrestrial sediment that diluted the Ir concentration. H_2O: Water content was measured in magnetic grains by PGAA which is very sensitive to hydrogen in small samples. The concentration is unusually high (Table 1) at all sites ranging from 0.7 wt.% (5.6 at.%) at Topper to 5.1 wt.% (28 at.% H) at Murray Springs. At Gainey the magnetic grains contain 3.2 wt.% (18 at.%) H2O compared to 0.8% wt.% (5 at.%) H in the adjacent sediment. Tektites and ET sources typically contain little H_2O so it is likely that the excess water has a terrestrial origin. The water appears to have been trapped inside the magnetic grains since they often explode when placed in a microwave oven. Large amounts of water (£20 wt.%) have also been observed in granite silicate melt inclusions (Thomas, 2000). If the impact occurred over water or ice, producing an explosion of steam, then water could be trapped in the hot ejecta as it solidified.

Fe, Ti, and Ni: The abundances of Fe, Ti, and Ni in magnetic grains from the YDB (Table 1) were determined by NAA and PGAA. At all sites except Gainey they are composed mainly of Fe(14-41 wt.%) and Ti(8-49 wt.%) with only 40-440 ppm Ni. This composition is very unusual since meteorites are typically enriched in Ni and depleted in Ti. At Gainey TiO_2/FeO=0.11 which is nearly o the crustal average TiO_2/FeO=0.13 (Rudnick and Gao, 2003). The average ratio for magnetic grains from other sites is TiO_2/FeO=0.73 which is much higher than for all known terrestrial or meteoritic sources. SEM/XRF analysis of 14 microspherules from four sites, including Gainey (Table 1), gives an average ratio TiO2/FeO=0.77 in good agreement with the magnetic grains.

Analyses of extraterrestrial magnetic grains and microspherules found in polar ice have yielded very different compositions. El Goresy (2004) reported that only one of 47 grains and spherules in Greenland ice contained measurable Ti (29.7 wt.%). Gounelle et al (2005) analyzed 67 Antarctic micrometeorites finding none with more than 0.2 wt.% TiO_2. A single large magnetic microspherule containing 26 wt.% TiO2 was found in the KT Maastrichtian bone bed (Mathur et al. 2005), and one particle ascribed to the Tunguska impact contained 75 wt.% Ti (Longo et al. 1994). Iyer et al (1997) summarized the average Ti concentrations in 202 volcanic spherules from the Pacific Ocean (0.7-7 wt.%) and from Central Indian Ocean Basin (0.3%). The only extraterrestrial source with a comparable ratio is Lunar Procellarum KREEP Terrane (PKT) with TiO_2/FeO»0.6 (Haskin et al. 2000).

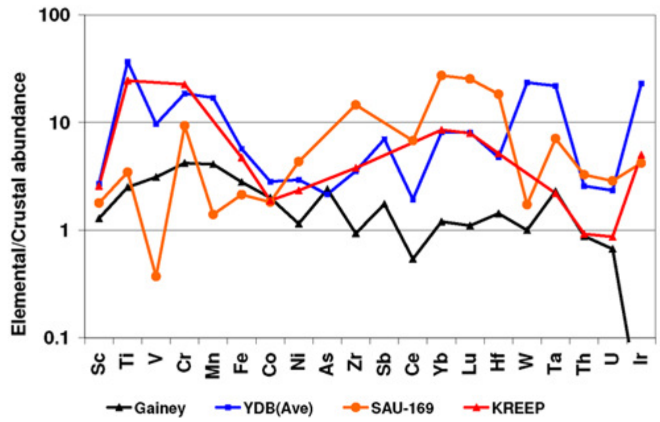

Figure 5. NAA/PGAA measurements of heavy element abundance in magnetic grains, normalized to crustal abundance, for the Gainey, MI Clovis site and in the YDB layer are compared with abundances in lunar Procellarum KREEP Terrane and lunar meteorite SAU-169. Gainey is most similar to crustal abundance and the YDB layer is enriched in heavy elements and comparable to lunar PKT and SAU- 169.

Heavy Elements: Fig. 5 shows the elemental composition for elements Sc to U, normalized to terrestrial abundance, in YDB magnetic grains determined by NAA and PGAA. These elements are all significantly enriched with respect to terrestrial abundance. The elemental composition is also compared to PKT values from Korotev et al. (2000), for elements heavier than Co in Apollo 12 regolith, and to Marvin and Walker (1978) for Ti, Cr and Fe in PKT lunar glass. The composition of the YDB magnetic grains is remarkably comparable to lunar PKT. Elemental abundances from lunar meteorite SAU-169 (Gnos et al. 2004) are also compared in Fig. 5. SAU-169 fell to Earth in Oman near the time of the YD impact and is believed to have come from the PKT. The composition of SAU-169 for elements heavier than Co is also similar to YDB magnetic grains, especially for Th and U, although the lighter element composition of SAU-169 is more terrestrial. The high abundance of Th and U in the magnetic grains explains the excess radioactivity that has been observed in the YDB layer.

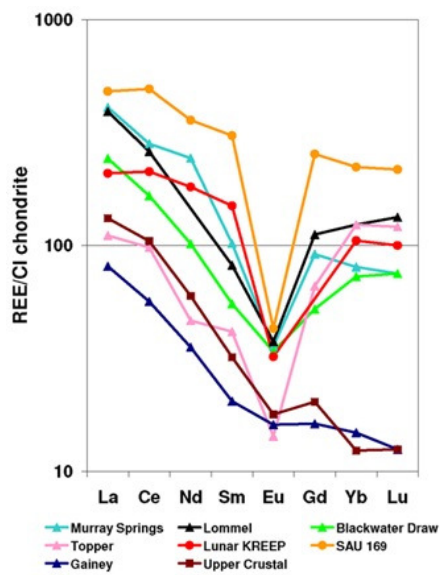

Figure 6. CI Chondrite normalized rare earth element (REE) concentrations in magnetic grains from various YDB layers are compared with crustal, lunar PKT, and SAU- 169 values. Magnetic grains from the Gainey Clovis site are very similar to crustal REE and those from other sites are very similar to the lunar PKT and SAU-169 showing a distinctive negative Eu anomaly.

Rare Earth Elements (REE): The REE abundances in magnetic grains from the YDB layer at several sites, normalized to CI Chondrite values, are compared with terrestrial, SAU-169, and lunar KREEP composition in Fig. 6. Gainey magnetic grains have REE abundances similar to terrestrial values. YDB magnetic grains, SAU-169, and lunar KREEP have higher ratios and all exhibit a negative Eu anomaly which is a signature of the PKT but not of other lunar basalts.

Potassium: The K_2O abundance in magnetic grains was measured with PGAA. Values were comparable at Gainey (2.0 wt.%) and other Clovis-age sites (0.3-2.5 wt.%). This is consistent with crustal abundance (2.8 wt.%) but higher than for lunar KREEP (0.4 wt.%) or SAU-169 (0.5 wt.%). The isotopic abundance of the naturally occurring radioactive isotope ^{40}K was measured by γ-ray counting and is summarized in Fig. 7. For 2 Clovis chert samples and 4 of 6 YDB sediment samples ^{40}K is enriched by factors of from 14±7% to 300±60%. The natural abundance of the isotope ^{40}K is only 0.0117% (Rosman and Taylor, 1998) and Voshage (1978) has shown that ^{40}K abundance is enriched by up to 1600°— in iron meteorites due to the spallation of Fe by cosmic rays. The enrichment of ^{40}K in the YDB is inversely proportional to the total K concentration in all samples except Lake Hind indicating that excess 40K deposited by the impact is diluted by terrestrial background. At Lake Hind the total concentration of K in the YDB is 2.7 wt.% which is significantly higher than either above or below (<0.01 wt.%) suggesting that K from the impact is highly concentrated in this layer. Similar enrichment in ^{40}K would be expected in the Fe-rich PKT sediments which appears to be confirmed by the discrepancy in Lunar Orbiter (40K) and "ground truth" (total K) abundance measurements (Gillis et al. 2004).

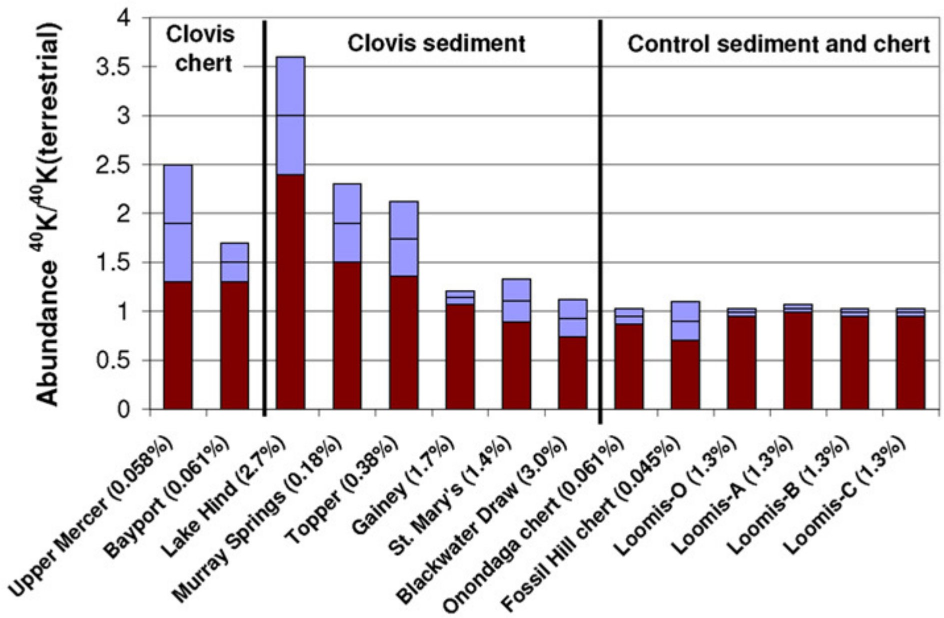

Figure 7. Abundance of ^{40}K in Clovis-age chert and sediment normalized to terrestrial values. Total potassium concentrations are given in parentheses following the sample identifications on the lower axis. Six control samples showed normal ^{40}K abundance and 6 of 8 samples from the YDB layer were enriched in ^{40}K.

4. Analysis of the Carbon Spherules, Nanodiamonds, Glass-like Carbon, Charcoal, Fullerenes and Soot.

Vesicular carbon spherules, glass-like carbon, charcoal, Fullerenes and soot all peak in the YDB layer. Charcoal and soot have long been recognized as markers of high temperature burning, but the carbon spherules, which contain nanodiamonds, and glasslike carbon appear to be new impact markers that are not widely recognized in the literature. Carbon Spherules and nanodiamonds: Highly vesicular carbon spherules, up 2 mm in diameter, are found throughout the YDB and are especially abundant at Gainey (1200 per kg), Lake Hind (180/kg) and in the Carolina Bays (140-1460/kg). The carbon spherules are often found together with copal spherules (Fig. 2) suggesting that they have a common origin in tree resin. Analysis of the carbon spherules by XRD indicates that they often contain a high density of nanodiamonds. West observed that carbon and copal spherules are found on the ground following intense forest fires and that they can be produced in by burning wood but these carbon spherules contain no nanodiamonds. Similar undated carbon spherules have been found in European soils that were also found by Yang et al (2008) to contain nanodiamonds. Kennett et al (2009) found cubic-, hexagonal-, octahedral-, and n-type nanodiamonds in carbon spherules and in YDB sediment from the Lake Hind, Murray Springs, and Bull Creek (Oklahoma). N-type nanodiamond concentrations in the carbon spherules ranged from 10-3700 ppb by weight or $>10^9$ per cm^3. In sediments free nanodiamonds peaked in the YDB sediment with concentrations of 100-200 ppb and no nanodiamonds were found in sediment above or below the YDB. N-nanodiamonds are not known to occur naturally but they have been found in meteorites (Grady et al. 1995). West found that if carbon spherules are produced in the laboratory under anoxic conditions they will form nanodiamonds. Similar conditions would occur following an extraterrestrial impact.

Table 2. PGAA Analysis of Carbon Spherules and Glass-like Carbon

Element	Carbon Spherules	Glass-like Carbon
H	5.6%	3%
B	65 ppm	10.2 ppm
C	86%	90%
N	1.9%	0.66%
Al_2O_3	2.1%	1.0%
SiO_2	2.3%	4.8%
S	0.4%	300 ppm
Cl	770 ppm	181 ppm
K_2O	0.12%	120 ppm
CaO	0.5%	0.49%
TiO_2	0.090%	0.067%
FeO	0.2%	0.08%
Cu	600 ppm	80 ppm
Cd	0.9 ppm	0.22 ppm
Sm	0.9 ppm	0.19 ppm
Gd	1.0 ppm	0.22 ppm

PGAA analysis of bulk carbon spherules from a Carolina Bay is shown in Table 2. The main composition is similar to tree resin ($C_{12}H_{20}O$). Significant quantities of SiO_2 (2.3 wt.%) and Al_2O_3 (2.1 wt.%) found in the carbon spherules may be due to contamination by the associated sediment. A large amount of nitrogen (1.9 wt.%) is found in the carbon spherules that greatly exceeds the quantity expected if it were simply from trapped air. It is notable that trace amounts of Ti and Fe with TiO2/FeO=0.45, consistent with the ratio in magnetic grains and microspherules, were found in the carbon spherules.

Carbon spherules from the Carolina Bays and Gainey were radiocarbon dated at the Keck Carbon Cycle AMS Facility at UC Irvine. These dates, summarized in Table 3, vary from 275 yr BP to 755 yr in the future and are inconsistent with their age inferred by the stratigraphy of the samples, strongly suggesting that the carbon spherules are enriched by a factor of »5 in ^{14}C. No natural process is known to enrich carbon in ^{14}C that much. It has been suggested that hydrogen in the comet might undergo a D+D fusion process on impact producing neutrons that would make ^{14}C in the atmosphere (Brown and Hughes, 1977; Kim, 2008), but this seems unlikely unless the comet's velocity were extraordinary (D'Alessio and Harms, 1988). Another possibility is that the impacting object was ejected by a recent near-Earth supernova in which case carbon is expected to be enriched in ^{14}C by 10^7 (Woosley and Weaver, 1995). No such object of sufficient density is known to be emitted by a supernova and a large velocity would be required for this object to reach Earth before the excess ^{14}C ($t_{1/2}$=5730 yr) had decayed.

Table 3. YDB Marker and Upper Midwestern Clovis-Age Site Radiocarbon Dates[+]

UCI-AMS#	YDB Site	Depth (cm)	Date (yr)	Clovis site	Date (yr)
	Carbon spherules			**Upper Midwest**	
29311	Blackville Bay	30	−755±15	Sandy Ridge, ON	735±65
29302	Sewell Bay	110	−400±15	Leavitt, MI-1	1100±600
29305	Bladen Bay	80	−180±20	Leavitt, MI-2	7886±116
29316	Gainey Clovis	20	−135±15	Alton, IN	1860
29297	Myrtle Bay	97	275±20	Thedford, ON	2130±230
	Woody debris			Gainey, MI	2830±175
29327	Myrtle Bay	163	−685±15	Zander, ON	3380±420
29328	Myrtle Bay	173	305±20	Potts, NY	3810
	Glass-like carbon			CB-North IL-1	3190±330
29318	Myrtle Bay 2	70	685±15	CB-North IL-2	4000±90
29309	Bladen Bay	173	2630±20	CB-North, IL-3	4180±40
29301	Sewell Bay	20	4230±15	Halstead, ON	6030±60
29308	Bladen Bay	122	5820±15	Sheriden Cave, OH	>12640
29299	Myrtle Bay	97	6395±25	Paleo Crossing, OH	12900±200
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		

† Schott (2007)

Glass-like Carbon: Pieces of glass-like carbon, up to several cm in diameter, have been found in the YDB layer at most sites with concentrations in sediment ranging from 0.01- 16 g/kg. Glass-like carbon doesn't exist naturally and the man-made varieties are shown to have a structure similar to Fullerenes (Harris, 2004). Nanodiamonds were found in a Carolina Bay sample. The PGAA analysis of glass-like carbon sample from the Carolina Bays is shown in Table 2. It is 90 wt.% C and analysis by ^{13}C NMR indicated that it is 87 at.% aromatic, 9 at.% aliphatic, 2 at.% carboxyl, and 2 at.% ether. PGAA shows that the sample contains significant amounts of SiO2 (4.8 wt.%) and Al_2O_3 (1.0 wt.%), probably from contamination by YDB sediment. A significant quantity of nitrogen (0.66 wt.%) and trace amounts of TiO2 (0.067 wt.%) and FeO (0.08 wt.%) were found. The ratio of TiO_2/FeO=0.8 is comparable to that found in magnetic grains and microspherules.

A sample from the Carolina Bays shown in Fig.8 was found to grade from glass-like carbon at one end to wood on the other. The wood was identified by Alex Wiedenhoft (private communication) as Yellow Pine, a species native to the Carolinas at the time of the YDB. Glass-like carbon can be produced by the thermal decomposition of cellulose at 3200 °C (Kaburagi et al. 2005) but such high temperatures would normally consume the entire tree. The composition of this sample is consistent with a tree that was impacted by a rapidly moving, high-temperature shockwave that produced glass-like carbon on only one side as it passed. The anoxic conditions following the shock wave would have stopped further burning.

Figure 8. A carbon sample from a Carolina Bay that varies from the shiny, melted appearance of glass-like carbon at the top to Yellow Pine on the

bottom. This can occur if the sample were exposed to the 3200 ° shockwave that "melted" one side of a tree but failed to destroy it entirely due to anoxic conditions behind the shockwave.

Radiocarbon dates for six glass-like carbon samples from the Carolina Bays are summarized in Table 2. Dates range from 685-8455 yr BP, much younger than the age inferred from their statigraphic context. The discrepancies are not as large as for the carbon spherules suggesting that these samples are predominantly composed of tree cellulose with additional 14C-rich carbon mixed into the glass-like carbon by the shockwave.

Charcoal: Excess charcoal was found in the YD layer at 8 of 10 Clovis-age sites and in all Carolina Bays tested. It was identified visually and by SEM based on its distinctive cellular structure. Concentrations ranged in sediment range from 0.06-11.63 g/kg. Radiocarbon dates range from 6565 yr BP to 510 yr into the future. These dates are consistent with the problematic radiocarbon dates reported at many Clovis-age sites in the Upper Midwest (735-7886 yr BP) that are summarized in Table 3.

The excess radiocarbon observed in the carbon spherules, glass-like carbon, and charcoal is also seen in the radiocarbon record (Reimer et al. 2004) as shown in Fig. 9. The sudden increase in D14C 12.9 ka ago that more than tripled the amount of radiocarbon in the atmosphere adding 1500 kg of ^{14}C (Schimel et al. 1995). The impact either produced or transported excess ^{14}C to Earth by a mechanism that remains elusive.

Fullerenes: Fullerenes were found in the YDB layer at three of four sites studied, Blackwater Draw, Murray Springs, and Daisy cave, and in glass-like carbon from the Carolina Bays. The Fullerene-like structure of the glass-like carbon (Harris, 2004) is consistent with the presence of Fullerenes in the YDB layer. Fullerenes in the glass-like carbon sample contain trapped helium with a $^{3}He/^{4}He$ ratio 84x that of air. This high abundance of ^{3}He is an indication of extraterrestrial origin.

Soot and PAHs: Soot was identified by SEM imaging, quantified particle analysis, and weighing. It is distinguished by its grape-like cluster morphology (Kroto, 1988). It was only observed in two of eight sites tested, Murray Springs (21±7 ppm) and a Carolina Bay (1969±167 ppm). Soot may have disappeared at most sites because it requires anoxic burial conditions to survive. It only forms in flames by direct condensation of carbon in the gas phase, requiring high temperatures, and has been observed in the K/T boundary (Wolbach et al. 1985). High-temperature burning also produces PAHs which were also found at the K/T boundary (Venkatesan and Dahl, 1989). They appear only in the YDB layer at Daisy Cave, Murray Springs, and Blackwater Draw, but neither above nor below it.

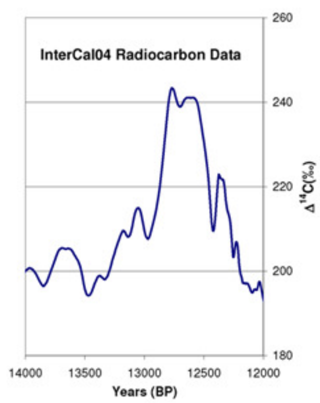

Figure 9. A sudden increase in atmospheric ^{14}C is seen in the INTERCAL04 radiocarbon calibration data (Reimer et al. 2004). The 4% increase in global radiocarbon is equivalent to a 200% increase in atmospheric ^{14}C (Schimel et al. 1995).

5. Discussion of the YD Impact

The geographic distribution of microspherules, magnetic grains, FeO, TiO_2, SiO_2, and H_2O found in the YDB layer is shown in Fig. 9. All of the markers except TiO_2 are much more abundant at Gainey and TiO_2 is more abundant at more distant sites. This distribution of markers is consistent with the airburst of a meteorite near the Great Lakes that deposited low velocity terrestrial debris near the impact site and high velocity, titanium-rich meteoritic debris at greater distances. This is confirmed by chemical composition of magnetic grains which is also terrestrial at Gainey and PKT-like elsewhere. The unusual composition of magnetic grains far from the Great Lakes suggests that they are mostly the exploded debris of the meteorite. High concentrations of H_2O in the magnetic grains are consistent with an impact occurring over the Laurentide Ice Sheet. Much of the impact debris would have been water from the glacier which leaves no permanent deposit and explains why the YDB impact layer contains so little terrestrial debris. The microspherules at Gainey have the same Fe/Ti composition as those at other sites which is very different from the Gainey magnetic grains. This suggests that they formed during from the meteorite in the initial explosion, were ejected to high altitudes, and fell to Earth over the entire Northern Hemisphere.

The average deposition of magnetite grains at the sites distant from the Great Lakes is »10 mg/cm^2. If we assume that this is the average deposition concentration of meteoritic material across the Northern Hemisphere then the mass of the impacting object would be 2.5°—10^{13} kg. A comet with this mass and a density of 0.5 g/cm3, similar to Shoemaker- Levy 9 (Solem, 1994), moving at 50 km/s would be 4.6 km-wide with an energy of 3°—10^{22} J (8°—106 mT of TNT). According to Toon et al (1997) an airburst at optimum height with this energy would cause extensive blast damage across an area the size of the United States. Simple calculations (Collins et al. 2005) indicate that a solid object with these dimensions and velocity and an impact angle of 25° should leave a shallow crater 20 km-wide and 0.7 km-deep. These calculations assumed an impact into 1 km of water, but an ice impact should leave a lesser crater. This crater could easily be hiding within the Great Lakes where the action of water rushing out of the failing glacier would have erased many of its features. If the impact were by a comet, which can be described as "an assemblage of a large number of spherical components bound together only by gravity" (Solem, 1994), it would likely have broken apart in the atmosphere leaving numerous smaller craters.

The impact would have produced a hot fireball that would immolate everything within sight. At greater distances high-speed, superheated ejecta would induce wildfires decimating forests and grasslands. The blast wave would have blown away the local atmosphere leaving a temporary vacuum and allowing cosmic rays to penetrate to the ground, possibly causing the tracks Topping observed in chert. Nearly 100% of the impact energy from the airburst goes into a high-temperature shock wave creating an overpressure of >4 psi with powerful winds >250 km/h (Toon et al. 1997) that would race cross the continent creating the impact debris-rich Carolina Bays as it passed. The temperature of the shock wave is recorded in formation of carbon spherules and glasslike carbon on the side of a tree. The winds from the shockwave are consistent with the orientation of the Bays and the theory that they were eolian in origin (Kaczorowski, 1976). The impact would have produced long term cooling effects coming from depletion of the ozone layer and injection of NOx, sulfates, water, dust, and soot into the atmosphere, compounding the cooling caused by the shutdown of the North Atlantic thermohaline circulation.

The affects of the impact would be devastating to plants, animals, and humans. Many sites show indications that Clovis people and extinct megafauna were present immediately before the YD impact event and neither survived. At Murray Springs the still articulated mammoth bones, Clovis tools, and a hearth are found beneath the black mat suggesting that mammoths were suddenly buried while in the process of being butchered. At the Wally's Beach kill-site 51 ppb Ir is found in sediment trapped inside an extinct horse skull suggesting rapid burial. Animals that survived the impact in protected niches would later succumb to insufficient food supplies, disease, or flooding triggered by the YD impact. The black mat covering them is composed of decaying plant and animal material and ash from the fires that ensued. Survivors would have faced a bleak landscape with little to eat and their numbers decimated.

The YD impact is supported by a large body of evidence from dozens of sites where hundreds of samples were collected and subjected to thousands of analyses. These data provide a consistent description of the impact event and its subsequent effects. The coincidental timing of the YD impact, megafaunal extinctions, failure of the Laurentide Ice Sheet, and the onset Younger Dryas cooling cannot be accidental. No other explanation is backed by such extensive experimental evidence and can explain all of these events. Still more needs to be learned about the curious chemical composition of the YDB layer, whether there is a connection to the lunar PKT, and why the carbon associated with the impact is so rich in ^{14}C.

6. Criticisms of the Younger Dryas Impact Theory

Many objections have been raised to the Younger Dryas impact theory. This is expected for a paradigm shifting hypothesis that invokes a catastrophic description to a relatively recent event on Earth. The criticisms have stimulated considerable discussion among the scientific community and in the media. Although it is not possible to address the uniformitarian bias held by some geologists opposed to the impact hypothesis, I will address some of the specific criticisms here.

The frequency of this impact should be 10^7 years so an occurrence 12.9 ka ago is unlikely. This impact frequency (Toon et al. 1997) is the probability for an impact by a comet large enough to cause continent wide damage in a single year. A more useful comparison is the probability that such an impact would occur during the past 30 ka which is 0.3%. Shoemaker (1998) has shown that based on lunar crater ages and recent increases in the accumulation of ^{3}He in deep sea sediments the recent impact rate may be an order of magnitude higher. This has been confirmed by Culler et al (2000) who estimate a recent impact increase by a factor of 3.7 from the distribution of lunar spherule ages. Therefore a more realistic estimate of the probability of an impact within the past 30 ka is of the order 1-3%. Clube and Napier (1984) proposed that this impact could be a debris spike from a Chiron-like progenitor of Encke's comet that has dominated the terrestrial environment for the past 20 ka. Since the YD impact was very different from the K/T impact and other known impacts, any calculation of its probability should be suspect.

The impact would have left a very large crater. Where is that crater? As discussed above the impact of a comet would leave a crater or craters that could easily be contained within the Great Lakes and greatly altered by the failure of the Laurentide Ice Sheet and rapid erosion by the sudden release of rushing waters. Schultz (2009) demonstrated with NASA's hypervelocity gun that if the impact occurred above a kilometer thick ice sheet, much of the energy would be absorbed by the ice and most of the ejecta would have been ice. Examination of the topography of the Great Lakes region shows that they form a great scar in an otherwise featureless landscape. They contain four of the deepest holes (craters?) in North America, three deeper that Death Valley (Fig. 10). Three of these holes line up nearly perfectly as if they were an impact crater chain. Charity Shoal, a 1 km crater in Lake Ontario, has already been identified as dating from the time of the YD impact (Holcombe et al. 2001).

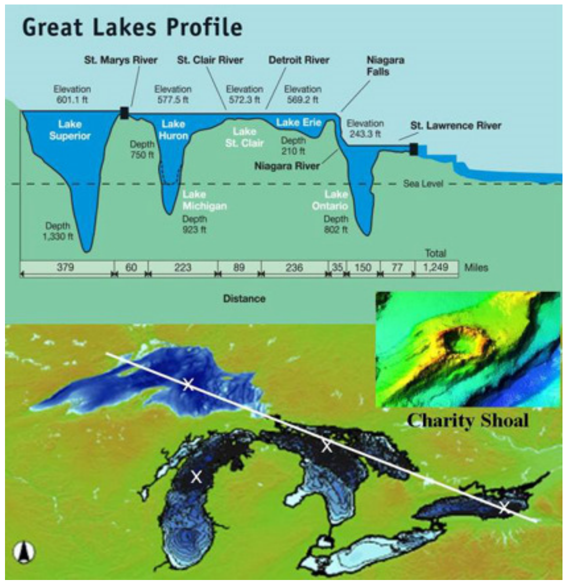

Figure 10. This profile of the Great Lakes shows that they are deep holes in the Earth. For lakes extend well below sea level and the bottoms of three lakes are deeper than Death Valley. The holes are too deep, up to 1330 ft (405 m), to have been caused by glacial or stream action and no recent tectonic activity has occurred in this region. Three of the holes are in a direct line much like crater chains that have previously been observed on the Earth, moon, and most recently the impact of comet Shoemaker-Levy on Jupiter. Charity Shoal (inset) is a 1-km crater in Lake Ontario known to have formed near the time of the YD impact. Diagram courtesy of Michigan Sea Grant.

The unusual chemistry of the YDB layer also suggests that the impact may have been by a different kind of object, possibly of very low density and/or unusually high velocity. A large, extended cloud or cluster of objects would likely have affected the entire solar system, possibly explaining the origin of the lunar PKT. This might be confirmed by looking for regions of PKT chemistry on other planets.

The microspherules found in the impact layer are dust from micrometeorite ablation fallout (Pinter and Ishman, 2008). This argument is invalid because no microspherules were found in well dated sediment layers above or below the YDB layer at any site. It is also incorrect because the YDB microspherules and magnetic grains have an unusual Fe/Ti composition while nearly all micrometeorites from the polar ice and other locations have a Fe or Fe/Ni composition. Approximately 30,000 tons meteoritic dust, 60 μg per m^2, fall to Earth each year. Assuming the YDB layer occurs at a depth of 30 cm, the concentration of meteoritic dust in 12.9 ka of sediment up to the surface would be »0.0015 g per kg. This is »0.1% of the magnetic grain concentration found in the YDB and can be ignored.

Analysis of lake sediments shows little impact evidence with only modest charcoal peaks at the time of the YD impact (Gill et al. 2009). Remarkably, Lininger (2008), from the same research group, found that "A fire peak occurs contemporaneously with the onset of the Younger Dryas climatic event at 12,900 cal yr BP, supporting the hypothesis of an extraterrestrial impact at that time." Firestone et al (2007) also found fewer impact markers in the Lake Hind samples than at other sites. This can be attributed to the low survival rate of some markers in lake environments. Carbon spherules are buoyant and may not always be found in lake sediments. Magnetite may disappear under reducing conditions or by biological action. Other markers including high concentrations of Ir and an excess abundance of ^{40}K have been found at Lake Hind.

Only modest production of charcoal was observed with the K/T impact. This has been attributed by Robertson et al (2004) to high-intensity, high-temperature fires that tend to destroy charcoal. The absence of substantial charcoal in the YD impact layer is therefore evidence for a fire of unusually high intensity which is consistent with the occurrence of high concentrations of soot in the YD impact layer and the highest levels of NH_4^+ in Greenland ice for over 100,000 years (Mayewski, 1993, 1997).

The Carolina Bays have been produced for 100,000 years by strong winds (Ivester et al. 2007). Unique impact markers found in the YDB layer are widely distributed throughout the Carolina Bay sediments at all 15 sites, suggesting that they are dated to 12.9 ka BP. Some bays, e.g. Waccamaw Bay (Stager and Cahoon, 1987), have been dated to that time. Sand grains from a Carolina Bay were dated by Optically Stimulated Luminescence (OSL) by Feathers (private communication) who found that their OSL ages ranged from 2-12 ka as shown in Fig. 11. Older OSL dates at Bays studied by Invester et al. (2007) may reflect inadvertent sampling of underlying, older sediment that may have shifted over time. Accurate OSL dates also require that the sediment grains were initially reset by exposure to light or intense heat. The YD impact shockwave could have mixed older, deeper sediments with those at the surface without necessarily resetting their OSL age leading to anomalous, older dates. The strikingly regular orientation of the Bays (Fig. 3) is inconsistent with their formation during major Atlantic storms under variable wind conditions, but is consistent with their formation by a shockwave coming from the Great Lakes. It is also likely that the Bay contents have shifted and have been mixed with newer sediments over time by the action of wind and water.

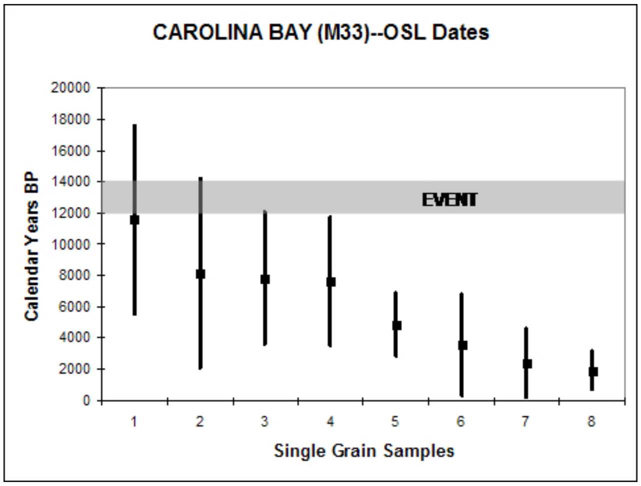

Figure 11. Optical Stimulated Luminescence (OSL) dates for 8 sand grains from a Carolina Bay indicate that the bay cannot be older that »12 ka. Variations in the dates suggest that the bay sediment has undergone mixing since its formation.

We find no evidence of magnetic grains and spherules peaking in the YD layer (Surovell et al. 2009). The YDB layer deposited at many sites across North America is only a few mm thick. Turbation by wind and water can destroy the YDB layer, change its position with respect to the YDB, or even split it into multiple thin layers. At about 20% of sites no evidence of the YDB layer remained. Tedious microstratigraphy is required to find the YDB impact layer which was often <2-3 mm wide. Broad sampling intervals near the YD layer used by Surovell et al (2009) have diluted their results considerably.

Nevertheless, close inspection of their evidence indicates that impact layer can still be weakly seen. They also selectively searched for highly spherical shiny microspherules thus excluding the dull, less spherical, and often pitted microspherules that we reported.

The difference in microspherules appearance may be due to their unusual Fe/Ti composition and weathering. Vance Haynes (private communication) reproduced our results at Murray Springs and numerous addition papers independently confirming the existence of the YDB layer at additional sites are pending.

We find no osmium or iridium anomalies in YD sediment (Paquay et al. 2009). We found high concentrations of Ir in magnetic grains but measurements were near experimental sensitivity limits for NAA in sediment. Still Ir was detected by an independent laboratory in 12 of 24 samples of magnetic grains or sediment from the YDB layer but in none of 62 samples from above or below the YDB. It is only possible to detect the Ir in sediments if the sampling is done very near the YDB layer requiring careful sampling by microstratigraphy. Ir from the impact is mostly contained in the magnetic grains which are present in the YDB at a concentration of 1-10g per kg of sediment. By comparison the K/T sediments were much richer in impact material containing 4.5 wt.% Fe (Alvarez et al. 1980) compared to 0.2-1 wt.% Fe in the YDB sediments. The K/T layer in Turkey has only 0.05-0.10 ppb Ir (Arakawa et al. 2003). Ir from YDB magnetic grains contained less Ir than typical iron meteorites suggesting that it is not a robust marker like in the K/T. Paquay et al (2009) did not sample with the proper microstratigraphy, mistakenly looked for it in the black mat, and still saw up to 0.117 ppb Ir at Lake Hind yet they failed to agree that it was enriched over terrestrial abundance. Beets et al (2008) found a distinct layer of non-radiogenic Os dated to 12,893 cal yr BP near the Lommel, Belgium site with $^{187}Os/^{188}Os=0.53\pm0.01$ which is much lower that adjacent layers where $^{187}Os/^{188}Os>1.1$.

The black mat is the impact layer, similar to the K/T layer. No, the black mat was deposited after the impact and is an algal mat mixed with ash from forest fires. This mat was likely produced by the decay of dead plant and animal remains after the impact. All of the extinct animals and the impact layer lie below the black mat. The K/T layer is the impact layer from an event about 100 times larger than the YD impact. Unlike the YD impact layer, which is very thin and invisible to the naked eye, the K/T impact layer is clearly visible and can be studied without separating the magnetic grains from the sediment.

7. Conclusions

12.9 ka ago a >4-km wide object exploded over the Laurentide Ice Sheet causing the extinction of numerous species of megafauna, smaller mammals, and birds, and the failure of the glacier. A flood of fresh water into the North Sea caused the shutdown of the North Atlantic thermohaline circulation which, coupled with the ejection of dust, ash, and water vapor into the atmosphere, led to >1000 years of Younger Dryas cooling.

The resulting impact layer is highly enriched in titanium with a composition comparable to lunar Procellarum KREEP Terrane and meteorite SAU-169 with a substantial excess abundance of ^{14}C. The impact may have produced the deepest holes in North America, at the bottom of the Great Lakes, and likely formed the Carolina Bays. The nature of the object that impacted Earth 12.9 ka ago remains a mystery so any estimate for the probability of this event is purely speculative. Efforts to confirm the YD impact have been successful at many new sites, and it is clear that only meticulous research done with an open mind can lead to a fuller understanding of what happened.

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