Oral Session

Session Title: PP33B. Younger Dryas Boundary: Extraterrestrial Impact or Not? II

Session Type: Oral

Chair: Allen West
Chair: Mark Boslough
Chair: Philippe F Claeys
Chair: Ted E Bunch

Location: 2006 (Moscone West)

Start time: Wed, Dec 16 - 1:40 PM

PP33B-01. Putting the Younger Dryas Cold Event into Context. *W. S. Broecker; G. Denton; R. Edwards; H. Cheng; R. B. Alley; A. Putnam* View Pres.	Wed, Dec 16 1:40 PM	No itinerary selected
PP33B-02. Are Nanodiamonds Evidence for a Younger Dryas Impact Event?. *A. West; J. Kennett; D. J. Kennett; T. E. Bunch; T. W. Stafford, Jr.; W. S. Wolbach* View Pres.	Wed, Dec 16 1:52 PM	No itinerary selected
PP33B-03. Airbursts in the Sky with Diamonds? Shock Limits to a Younger Dryas Impact.. *H. J. Melosh* View Pres.	Wed, Dec 16 2:04 PM	No itinerary selected
PP33B-04. Lost Impacts. *P. H. Schultz; A. M. Stickle* View Pres.	Wed, Dec 16 2:16 PM	No itinerary selected
PP33B-05. Cosmic impact: What are the odds?. *A. W. Harris* View Pres.	Wed, Dec 16 2:28 PM	No itinerary selected
PP33B-06. High resolution Osmium isotopes in deep-sea ferromanganese crusts reveal a large meteorite impact in the Central Pacific at 12 ± 4 ka . *M. Sharma; C. Chen; B. P. Jackson; W. Abouchami* View Pres.	Wed, Dec 16 2:40 PM	No itinerary selected
PP33B-07. No support from osmium isotopes for an impact event at	Wed,	No

the Bølling-Allerød/Younger Dryas transition. *F. Paquay; G. E. Ravizza* View Pres.	Dec 16 2:52 PM	itinerary selected
PP33B-08. Testing Younger Dryas ET Impact (YDB) Evidence at Hall's Cave, Texas. *T. W. Stafford; E. Lundelius; J. Kennett; D. J. Kennett; A. West; W. S. Wolbach* View Pres.	Wed, Dec 16 3:04 PM	No itinerary selected
PP33B-09. Pleistocene Megafaunal Collapse in North America Preceded the Younger Dryas: Evidence from the Midwest. *J. L. Gill; J. Donnelly; S. T. Jackson; K. B. Lininger; J. P. Marsicek; G. Robinson; B. M. Simonson; J. W. Williams* View Pres.	Wed, Dec 16 3:16 PM	No itinerary selected
PP33B-10. Summary of impact markers and potential impact mechanisms for the YDB impact event at 12.9 ka. *T. E. Bunch; P. H. Schultz; J. H. Wittke; A. West; J. Kennett; D. J. Kennett* View Pres.		

ID#	PP33B-01
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 1:40 PM - 1:52 PM

Putting the Younger Dryas Cold Event into Context

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The Younger Dryas event is by far the best studied of the millennial-scale cold snaps of glacial time. Yet its origin remains a subject of debate. The long-held scenario that the Younger Dryas was a one-time outlier triggered by a flood of water stored in proglacial Lake Agassiz has fallen from favor due to lack of a clear geomorphic signature at the correct time and place on the landscape. The recent suggestion that the Younger Dryas was triggered by the impact of a comet has not gained

traction. Instead, evidence from Chinese stalagmites suggests that, rather than being a freak occurrence, the Younger Dryas is an integral part of the deglacial sequence of events that produced the last termination on a global scale.

ID#	PP33B-02
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 1:52 PM - 2:04 PM

Are Nanodiamonds Evidence for a Younger Dryas Impact Event?

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Nanodiamonds (NDs), including hexagonal diamonds (lonsdaleite) have been discovered at the Tunguska impact site and in the Cretaceous-Tertiary (K/T) boundary layer, which also contains cubic diamonds. Similarly, for the Younger Dryas boundary layer (YDB) that dates to the onset of the Younger Dryas (YD) cooling event at ~12.9 ka, NDs (cubics and lonsdaleite) are found broadly at multiple locations over North America and Europe. The NDs are proposed to result from a cosmic impact event that triggered widespread biomass-burning, which produced peaks at multiple sites in charcoal, grape-cluster soot, carbon spherules (CS), glass-like carbon, ammonium, and nitrate at the onset of the YD. The question is whether or not a cosmic impact is the best or only explanation for the YDB nanodiamonds. For example, could volcanism or intense wildfires have produced them? **WILDFIRES:** There is evidence for widespread fires at 12.9 ka: (1) The YDB also contains variable concentrations and sizes of CS, which are carbon-rich spheres produced through intense heat in high-stand wildfires. (2) Greenland ice cores exhibit spikes in ammonium and nitrate at the YD onset, that are interpreted as proxies for biomass-burning and collectively form the largest such peak known from late Quaternary ice cores. (3) Nearly all of 74 North American lakes examined exhibit peaks in charcoal representing evidence for wildfires at or close to ~12.9 ka, within the limits of radiocarbon dating. (4) High levels of soot have been detected in the YDB layer at five sites across North America (CA, AZ, OK, TX, and SC). **NANODIAMONDS:** For Tunguska, K/T

sites, and the YDB, NDs have been found either embedded within or closely associated with CS. Experimental research demonstrates that ND formation requires extreme physical conditions generated either in the laboratory or during an ET impact, and not otherwise found on Earth's surface. These conditions include transient high temperatures, hypoxic atmospheric conditions, and rapid quenching, thus excluding regular wildfires, where oxic conditions would destroy NDs. The available evidence supports formation of nanodiamonds by cosmic impact at 12.9 ka for the following reasons: (A) Lonsdaleite has never been found associated with any volcanic or igneous rocks or with mantle-derived terrestrial diamonds; (B) Lonsdaleite has been found only inside meteorites or impact craters; (C) NDs have never been found in association with non-impact wildfires; (D) No CS that contain NDs have been observed above or below known impact boundaries, e.g., the K/T and Tunguska layers; (E) In the entire geologic record, there are only two known continental layers containing both NDs and soot – the K/T boundary and the YDB. Thus, existing aggregate evidence supports an as-yet undefined cosmic event as the most compelling explanation for the YDB, and it argues against wildfires or volcanism as alternative causes.

ID#	PP33B-03
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 2:04 PM - 2:16 PM

Airbursts in the Sky with Diamonds? Shock Limits to a Younger Dryas Impact.

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Firestone, Kennett, West and others recently suggested that the Younger Dryas event, with its associated megafaunal extinctions, was precipitated by an extraterrestrial impact somewhere in North America, on or above the Laurentide ice sheet. Evidence initially put forward in favor of this hypothesis included elevated levels of iridium, microspherules and fullerenes in the "Black Mat" layer present at many Clovis cultural sites, although no impact crater has been found. While this evidence is presently strongly disputed by other investigators, the proponents of this idea currently cite the occurrence of nannodiamonds, particularly of the hexagonal Lonsdaleite variety, as definitive evidence of impact-generated shock, and suggest that no crater was formed because the impactor was a dispersed cometary object that exploded in the atmosphere. Such diamonds have been previously reported

associated with terrestrial impacts, including Chicxulub, Ries Crater and Popagai. Observations at the Ries indicate that diamonds form only at shock pressures between 45 and 55 GPa, while at Popagai the range is 35 to 50 GPa. While these pressures are readily attained in the impact of a solid body on the Earth's surface, it is much more difficult to attain them in an airburst because air is so easily compressed. Estimates from both the stagnation pressure upon entry and a planar impact computation using the measured Hugoniot parameters of air and the Murchison chondrite show that the minimum impact velocity that can yield these transformation pressures in chondritic material is more than 200 km/sec (independent of impact angle), well beyond the possible impact velocity of an object bound to the solar system. In another scenario it was suggested that the impact occurred on the ice sheet itself but did not penetrate the ca. 3 km thick ice mantle. However, this limits the size of the impactor to less than 1 km diameter. Many impacts of this size have occurred in the past (the average recurrence interval is about 1 per Myr), but no extinctions are associated with these events. Indeed, for an impact on the Laurentide ice sheet to ignite fires in Southern Arizona by thermal radiation from its fireball, approximately 5000 km from the impact site, a projectile almost 100 km in diameter would be required! Such an impact would have wiped out all life on the Earth except microbes, not just the megafauna. I thus conclude that there is no plausible scenario in which the Younger Dryas event was caused by an impact and suggest instead that the formation of nannodiamonds by non-impact processes (such as forest fires) simply needs to be better understood.

ID#	PP33B-04
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 2:16 PM - 2:28 PM

Lost Impacts

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The absence of a clearly identified crater (or craters) for the proposed YDB impact has raised questions concerning the reality of such an event. Geologic studies have identified impact deposits well before recognizing a causative crater (e.g., Chicxulub and Chesapeake Bay); some have yet to be discovered (e.g., Australasian tektite strewnfields). The absence of a crater, therefore, cannot be used as an argument against the reality of the YDB impact (and its possible consequences).

The study here addresses how a large on-land impact during the late Pleistocene or early Holocene could avoid easy detection today. It does not argue the case for a YDB impact, since such evidence must come from the rock record.

During the late Pleistocene, the receding Laurentide ice sheet still covered a significant portion of Canada. While a large (1km) body impacting vertically (90°) would penetrate such a low-impedance ice layer and excavate the substrate, an oblique impact couples more of its energy into the surface layer, thereby partially shielding the substrate. Three approaches address the effectiveness of this flak-jacket effect. First, hypervelocity impact experiments at the NASA Ames Vertical Gun Range investigated the effectiveness of low-impedance layers of different thicknesses for mitigating substrate damage. Second, selected experiments were compared with hydrocode models (see Stickle and Schultz, this volume) and extended to large scales. Third, comparisons were made with relict craters found in eroding sediment and ice covers on Mars.

Oblique impacts (30 degrees) into soft particulates (no. 24 sand) covering a solid substrate (aluminum) have no effect on the final crater diameter for layer thicknesses exceeding a projectile diameter and result in only plastic deformation in the substrate. In contrast, a vertical impact requires a surface layer at least 3 times the projectile diameter to achieve the same diameter (with significant substrate damage). Oblique impacts into ice and plasticene layers over clear acrylic blocks allow assessing internal damage. These experiments reveal that low-impedance surface layers approaching 1 to 2 projectile diameters effectively shield the substrate from shock damage for impact angles less than 30 degrees.

Missing craters (and relict crater roots) within ice-rich deposits on Mars illustrate the rapid erasure the impact record. Numerous small pedestal craters (crater diameter < 5km) occur at high latitudes and reflect the cyclic expansion and disappearance of polar ice/dust deposits up to 0.5 km thick. Much larger examples (> 50km), however, occur at low latitudes but are localized in certain regions where even thicker deposits (locally >2km) have been removed, uncovering a preserved Noachian landscape. Crater statistics further document this missing cratering record.

Thick Pleistocene ice sheets on Earth would have played a similar role for the removal of terrestrial cratering record. We calculate that a crater as large as 15km in diameter formed by an oblique impact could have been effectively erased, except for dispersed ejecta containing shocked impactor relicts and a disturbed substrate. While plausible, evidence for specific missing events (e.g., the proposed YB impact) must be found in still-preserved ice layers and sediments.

ID#	PP33B-05
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 2:28 PM - 2:40 PM

Cosmic impact: What are the odds?

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Firestone et al. (PNAS 104, 16016-16021, 2007) propose that the impact of a ~4 km diameter comet (or multiple bodies making up a similar mass) led to the Younger Dryas cooling and extinction of megafauna in North America, 12,900 years ago. Even more provocatively, Firestone et al. (Cycle of Cosmic Catastrophes, Bear & Co. Books, 2006, 392pp), suggest that a nearby supernova may have produced a comet shower leading to the impact event, either by disturbing the Oort Cloud or by direct injection of 4-km comet-like bodies to the solar neighborhood. Here we show: (a) A supernova shockwave or mass ejection is not capable of triggering a shower of comets from the Oort Cloud. (b) An Oort Cloud shower from whatever cause would take 100,000 years or more for the perturbed comets to arrive in the inner solar system, and the peak flux would persist for some hundreds of thousands more years. (c) Even if all 20 solar masses or so of ejected matter from a SN were in the form of 4-km diameter balls, the probability of even one such ball hitting the Earth from an event 100 light years away would be about 3e-5. (d) A 4-km diameter ball traveling fast enough to get here from 100 LY away in some tens of thousands of years would deliver the energy of a 50 km diameter impactor traveling at typical Earth-impact velocity (~20 km/sec). We review the current impact flux on the Earth from asteroids and comets, and show that the probability of an impact of a 4-km diameter asteroid in an interval of 13,000 years is about one in a thousand, and the probability of a comet impact of that size is a few in a million. An "impact shower" caused by the injection or breakup of comets or asteroids in the inner solar system by whatever means would take tens to hundreds of thousands of years to clear out, thus the population of NEOs we see now with our telescopic surveys is what we’ve had for the last few tens of thousands of years, at least. Faced with such low odds, the evidence that such a large cosmic impact is the cause of the Younger Dryas boundary and cooling, and that there is no other possible cause,

needs to be extraordinary indeed.

ID#	PP33B-06
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 2:40 PM - 2:52 PM

High resolution Osmium isotopes in deep-sea ferromanganese crusts reveal a large meteorite impact in the Central Pacific at 12 ± 4 ka

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Ferromanganese crusts grow by incorporating metals from ambient seawater and are shown to be faithful recorders of ocean paleochemistry. We studied a well-dated crust (VA 13/2) from the Central Pacific with the aim to provide a high resolution record of glacial-interglacial variations in the seawater Os isotope composition. The uppermost 1.5 mm section of the crust was sampled at every 50 μm with an 8 mm diameter drill-bit that was mounted on a high precision lathe. This corresponds to a time resolution of 4 ka for the first 550 μm and of 8 ka for the rest on the basis of ^{230}Th$_{excess}$ dating. Surprisingly, the Os contents and isotope ratios in the crust appear to be compromised between 50 and 100 μm by contact with a source that is highly enriched in Os but with low ^{187}Os\$^{188}$Os ratio. The depth corresponds to an age of 12 ± 4 ka and in comparison to a background seawater isotope ratio of 0.93-1.02, at this time the crust shows an isotope ratio of 0.24 suggesting input of meteorite derived Os. We prepared a thick-section of the crust to investigate whether the Os signal is associated with the presence of extraterrestrial (ET) particles. We found using optical microscopy and LA-ICP-MS that there are no large ET particles and that the Os enrichment of the crust is confined to within 100 μm of the surface. This suggests that the crust received meteorite-derived Os as extremely small particles. Investigations of surface scrapes of other crusts in the vicinity of VA 13/2 helped us define a large area in the Pacific with ^{187}Os\$^{188}$Os ratios lower than that estimated for the ambient seawater. We infer that the Central Pacific was a site of deposition of Os resulting from dust cloud following a meteorite impact at 12 ± 4 ka that suppressed the ^{187}Os\$^{188}$Os ratios of the crusts. Using the distribution of the Fe-Mn crusts whose surface-scrapes display ^{187}Os\$^{188}$Os ratios much less than ambient seawater (0.9 or less) we find that the meteorite could be up to 100 m in diameter. By examining a number of sites in North America and a site in Europe Firestone et al. (2007) proposed

that the Younger Dryas cooling event, which began at 12,900 years ago, was triggered by multiple cometary airbursts and/or impacts. If so, it is possible that a fragment of the impactor may have blown up over the Pacific. Higher resolution studies of marine sediments would be needed to confirm this observation.

ID#	PP33B-07
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 2:52 PM - 3:04 PM

No support from osmium isotopes for an impact event at the Bølling-Allerød/Younger Dryas transition

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The hypothesis that an extraterrestrial (ET) impact as a triggering mechanism for the abrupt Bølling-Allerød/Younger Dryas climatic transition, the North American megafaunal extinction and the demise of the Clovis culture still remains controversial. Reports of elevated iridium concentrations (> several ng/g) measured in magnetic grains and bulk sediments are used in previous work to argue that a chondritic bolide vaporized upon impact, or fully exploded into the atmosphere. If such a scenario is correct, high Ir concentrations are expected to be accompanied by a systematic decrease in the 187Os/188Os ratios toward unradiogenic, chondrite-like values, reflecting an ET platinum group element (PGE) component. In our study, Os, Ir and Pt were pre-concentrated from 5-20g of powdered samples by NiS fire assay after spiking the samples with a tracer solution enriched in 190Os, 191Ir and 198Pt. Large sample weights were used in order to minimize the nugget effect. Analyses of seven of the same black mat layers investigated in the original reports (Firestone et al. 2007), failed to reproduce previously reported high Ir concentrations, and yielded high 187Os/188Os ratios (1.00-1.90) that are typical of a crustal signature rather than an extraterrestrial one. In addition, a high-resolution study of 187Os/188Os ratios and Os and Ir concentrations in bulk sediments from two ocean margin sites where the Younger Dryas (YD) onset is clearly established by multiple proxies (DSDP 480, Guaymas Basin; ODP 1002C, Cariaco Basin) failed to detect any ET-PGE enrichment anomaly or systematic 187Os/188Os excursion to low ratios at the onset of the YD. Rather measured 187Os/188Os ratios remained within a few percent of present-day seawater 187Os/188Os across the BA/YD

transition at both of the marine sites. These results undermine previous claims of a chondritic projectile. Moreover they are difficult to reconcile with the impact of a body from any known meteorite class because differentiated, PGE-depleted meteorites are not known to contain nannodiamonds. The absence of an impact crater makes it difficult to argue that PGEs were somehow separated from nanodiamonds during an impact event. This leads us to conclude that the occurrence of nannodiamonds within carbon spherules does not constitute robust evidence of an impact, as previously suggested. Further we speculate that the wide spread occurrence of nannodiamonds at the onset of the YD is more likely to be the result of a still to be identified terrestrial process, perhaps related to wild fires.

ID#	PP33B-08
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Testing Younger Dryas ET Impact (YDB) Evidence at Hall's Cave, Texas

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Hall's Cave, Kerrville County Texas, 167 km WSW of Austin, provides a unique opportunity for testing the presence of a chronostratigraphic datum (YDB layer) containing rare and exotic proxies, including nanodiamonds, aciniform soot, and magnetic spherules, the origins of which remain controversial, but possibly derive from a cosmic impact ~12,900 CAL BP. The karst-collapse cave in Cretaceous limestone on the Edwards Plateau contains ≥ 3.7 m of stratified clays grading to clayey silts recording continuous deposition from 16 ka RC yr to present. The cave's small catchment area and mode of deposition were constant, and the stratigraphy is well dated based on 162 AMS ^{14}C dates from individual vertebrate fossils, snails, charcoal, and sediment chemical fractions. The cave sequence contains an abundant small animal vertebrate fossil record, exhibiting biostratigraphic changes, and

the timing of the late Pleistocene megafaunal extinction is consistent with that elsewhere in North America. At 151 cm below datum is the extremely sharp, smooth contact separating lower, dusky red (2.5YR3/2) clays below from overlying dark reddish brown (5YR3/3) clays (forming a 20-cm-thick dark layer) and dating to 13,000 CAL BP, at or close to the age of the YDB datum elsewhere. This appears to be the most distinctive lithologic change of the deglacial sequence. Sediments at or within 10 cm of this contact contain the local extinction of 4 species of bats, the local extinction of the prairie dog (Cynomys sp.) and perhaps other burrowing mammals in response to decrease in soil thickness, and the uppermost occurrence of 6 late Pleistocene megafaunal taxa that, although rare in the cave, do not extend younger than 12.9 ka. We collected and analyzed sediments at high resolution above and below the distinct lithologic contact at 151 cm. The red clays from 151 to 153 cm and immediately preceding the lithologic contact contain an abundance of nanodiamonds (5 different allotropes), aciniform soot at 2400 ppm, magnetic spherules, and carbon spherules, all of which we interpret as evidence for a unique chronostratigraphic marker (YDB) in the Western Hemisphere. Because the age of this horizon is ~ 13,000 CAL BP, we interpret the age of the event as the beginning of the Younger Dryas cooling. Regional soil erosion began ~15,000 CAL BP and continued until 7000 CAL BP, but dating suggests that there is no discontinuity or hiatus in deposition, and thus, the exotic materials in that layer are not considered to be erosional accumulations. Future analyses include sub-centimeter sampling over the YD boundary, quantification of nanodiamonds and other event-proxies within 1000 yr of the boundary and in sediments several 1000 years older and younger, continued refinement of the AMS ^{14}C record to determine within 50 yr the location of 12,900 CAL BP datum and high resolution analysis of small animal biostratigraphy.

ID#	PP33B-09
Location:	2006 (Moscone West)
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Pleistocene Megafaunal Collapse in North America Preceded the Younger Dryas: Evidence from the Midwest

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The recent Younger Dryas (YD) impact theory suggests that an extraterrestrial impact event at 12,900 calendar years BP was responsible for rapid and widespread environmental change, including the extinction of the Pleistocene megafauna. Evidence for such an event is expected to be preserved in lake sediments; lakes are robust archives of environmental change, including abrupt events such as the YD. Sporormiella, a dung fungal proxy for megafaunal presence, has recently been added to classic lake sediment proxies such as pollen and charcoal. Sporormiella spores have been found to be abundant in Pleistocene deposits and mostly absent during the Holocene until the historic introduction of domestic grazers, and are therefore a suitable proxy for Pleistocene herbivory regimes.

At Appleman Lake, IN, fossil pollen, charcoal, and Sporormiella were analyzed to reconstruct changes in vegetation, fire regime, and megafaunal presence. The Sporormiella record indicates that Pleistocene megaherbivores declined from 14.6 to 13.7 ka calendar BP, well before the onset of Younger Dryas cooling and the proposed impact event. However, these data are consistent with the oldest well-dated evidence of pre-Clovis human presence from butchered mammoth remains in the Midwest.

Immediately following the Sporormiella decline, pollen and charcoal data indicate shifts in plant community composition and an increase in fire frequency, possibly due to the release of palatable hardwood taxa and a build-up of landscape biomass following the local extirpation of herbivores. While the onset of the decline does correspond with Bølling-Allerød warming, the mechanism for the decline does not appear to be vegetation-induced habitat loss.

Additionally, sediment cores from Appleman and Spicer Lakes, IN, and Silver Lake in Ohio have been analyzed for evidence of an extra-terrestrial impact, including mineral spherules, charcoal peaks, ET-associated elements, magnetic grains, and loss-on-ignition. Our sites are well-situated to record regional evidence of an impact event in the Great Lakes region; however, no physical indicators of an impact have been found thus far. Paleovegetation analyses of Spicer and Silver Lake sediments are currently in progress to determine whether the timing and patterns of extinction and landscape change repeat across sites.

ID#	PP33B-10
Location:	2006 (Moscone West)
Time of Presentation:	Dec 16 3:28 PM - 3:40 PM

Summary of impact markers and potential impact mechanisms for the YDB impact event at 12.9 ka

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Until the announcements of a possible impact event (Firestone et al. 2007; Kennett et al., 2009a; 2009b) at the beginning of the Younger Dryas (YD) around 12.9 ka, the KT impact layer (KTB) that resulted from the Chicxulub impact at 65 mya was the only geological boundary layer known to contain coeval peaks in various impact markers, including diamonds. Here, we compare impact markers from the KTB, YD boundary layer (YDB), and the 1908 Tunguska airburst layer (TAL). First order markers, related to impact and biomass burning, include: magnetic spherules, carbon spherules, nanodiamonds (cubic and lonsdaleite), iridium anomalies, charcoal, fullerenes (with high ^{3}He to ^{4}He ratio), grape-like soot, and widespread extinctions. Observations and analytical data for the YDB are consistent with all of the KTB markers, while the last three markers are unknown or inconclusive for the Tunguska layer. Selected markers for cratering events, e.g, Chicxulub, are: a visible crater, shocked minerals, impact breccia, and microtektites. None of these are known for the YD event or Tunguska. The discussion here is limited to possible origins of the impact markers and not with impact consequences (climate change, extinctions, etc.). Several origins may account for impact materials in the YDB: (1) An extraordinary accretion of micrometeorites (Pinter and Ishman, 2008). However, this is inconsistent with YDB carbon spherule compositions, including the large concentrations of nanodiamonds found embedded in those carbon spherules. (2) Oblique impact(s) into the Laurentide Ice Sheet. This model is consistent with the lack of a visible crater and apparent lack of cratering markers (above), and yet also provides for

shock production of the many cubic nanodiamonds and lonsdaleite found in the YDB. (3) Impact-induced aerial burst. e.g, Boslough and Crawford (2007); Shuvalov (2008). The lack of high shock pressures in an aerial detonation does not necessarily preclude the formation of cubic and hexagonal diamonds, as shown by Maruyama et al. (1993), who made hexagonal and cubic diamonds by a CVD process from a high-temperature plasma atmosphere (13,000°C) under pressure conditions similar to those in an aerial burst. The Tunguska event is commonly accepted as the result of a near-surface aerial burst and has many similarities to the YD event. (4) Comet grazing of the atmosphere (Drobysheski, 2009), involving nearly tangential entry of a comet into the Earth's atmosphere with partial detonation and melting followed by escape of the unexploded nucleus into space. This has the net effect of an atmosphere-penetrating aerial burst followed by global fallout of detonation products. Three of the four above scenarios are plausible.