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The Younger Dryas impact hypothesis: A requiem

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ABSTRACT

The Younger Dryas (YD) impact hypothesis is a recent theory that suggests that a cometary or meteoritic body or bodies hit and/or exploded over North America 12,900 years ago, causing the YD climate episode, extinction of Pleistocene megafauna, demise of the Clovis archeological culture, and a range of other effects. Since gaining widespread attention in 2007, substantial research has focused on testing the 12 main signatures presented as evidence of a catastrophic extraterrestrial event 12,900 years ago. Here we present a review of the impact hypothesis, including its evolution and current variants, and of efforts to test and corroborate the hypothesis.

The physical evidence interpreted as signatures of an impact event can be separated into two groups. The first group consists of evidence that has been largely rejected by the scientific community and is no longer in widespread discussion, including: particle tracks in archeological chert; magnetic nodules in Pleistocene bones; impact origin of the Carolina Bays; and elevated concentrations of radioactivity, iridium, and fullerenes enriched in ^{3}He. The second group consists of evidence that has been active in recent research and discussions: carbon spheres and elongates, magnetic grains and magnetic spherules, byproducts of catastrophic wildfire, and nanodiamonds. Over time, however, these signatures have also seen contrary evidence rather than support. Recent studies have shown that carbon spheres and elongates do not represent extraterrestrial carbon nor impact-induced megafires, but are indistinguishable from fungal sclerotia and arthropod fecal material that are a small but common component of many terrestrial deposits. Magnetic grains and spherules are heterogeneously distributed in sediments, but reported measurements of unique peaks in concentrations at the YD onset have yet to be reproduced. The magnetic grains are certainly just iron-rich detrital grains, whereas reported YD magnetic spherules are consistent with the diffuse, non-catastrophic input of micrometeorite ablation fallout, probably augmented by anthropogenic and other terrestrial spherular grains. Results here also show considerable subjectivity in the reported sampling methods that may explain the purported YD spherule concentration peaks. Fire is a pervasive earth-surface process, and reanalyses of the original YD sites and of coeval records show episodic fire on the landscape through the latest Pleistocene, with no unique fire event at the onset of the YD. Lastly, with YD impact proponents increasingly retreating to nanodiamonds (cubic, hexagonal [lonsdaleite], and the proposed n-diamond) as evidence of impact, those data have been called into question. The presence of lonsdaleite was reported as proof of impact-related shock processes, but the evidence presented was inconsistent with lonsdaleite and consistent instead with polycrystalline aggregates of graphene and graphane mixtures that are ubiquitous in carbon forms isolated from sediments ranging from modern to pre-YD age. Important questions remain regarding the origins and distribution of other diamond forms (e.g., cubic nanodiamonds).

In summary, none of the original YD impact signatures have been subsequently corroborated by independent tests. Of the 12 original lines of evidence, seven have so far proven to be non-reproducible. The remaining signatures instead seem to represent either (1) non-catastrophic mechanisms, and/or (2) terrestrial rather than extraterrestrial or impact-related sources. In all of these cases, sparse but ubiquitous materials seem to have been misreported and misinterpreted as singular peaks at the onset of the YD. Throughout the arc of this hypothesis, recognized and expected impact markers were not found, leading to proposed YD impactors and impact processes that were novel, self-contradictory, rapidly changing, and sometimes defying the laws of

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physics. The YD impact hypothesis provides a cautionary tale for researchers, the scientific community, the press, and the broader public.

Contents

1. Introduction

A recent and controversial theory attributes the onset of the Younger Dryas (YD) climate interval, extinction of large mammalian fauna across North America, demise of the North American Clovis culture, and a range of other effects ~12,900 years ago to an extraterrestrial impact event (Firestone et al., 2007a; Kennett et al., 2009a,b). This hypothesis entered widespread scientific discussions at the May, 2007 meeting of the American Geophysical Union in Acapulco, Mexico. Since then, the YD impact hypothesis (YDIH) has been the subject of on-going research across a broad range of disciplines, several publications (supportive as well as skeptical), and remarkable attention in the popular media. In technical circles, some disciplines have remained critical of the hypothesis (e.g., meteoritics and impact science), whereas others have seen broader acceptance of a catastrophic impact 12,900 years ago (e.g., archeology). Media coverage has included numerous print articles worldwide, at least three television documentaries (for *National Geographic*, *Nova*, and *History Channel*), and a variety of on-going Web-based commentary. Now, after three years, sufficient time has elapsed and sufficient independent research has taken place to thoroughly review the YD hypothesis, evaluate the range of evidence presented both in support and against the proposed impact, and assess some broader questions posed by the YD impact debate.

1.1. The hypothesis

The end of the Pleistocene, following the Last Glacial Maximum (LGM), was a period of rapid and dramatic global change. Post-glacial warming during the Bølling–Allerød period reversed starting about 12,900 cal BP (calibrated years before present), with colder conditions prevailing during the ~1300-year Younger Dryas (YD) interval (Broecker et al., 2010; Meltzer and Holliday, 2010). In North America, an estimated 33 genera of mammalian megafauna (fauna > 100 kg; e.g., mammoths, mastodons, giant short-faced bear, saber-tooth tigers; Barnosky et al., 2004) went extinct at about this time, followed shortly thereafter by extinction of ~50 mammalian genera in South America (Barnosky et al., 2004; Fiedel, 2009). The interval between the LGM and the YD also coincided with the arrival and dispersal of Paleoindians through North and South America. The beginning of the YD coincides approximately with the end of the Paleoindian Clovis-type lithic technology (Haynes, 2010; Meltzer and Holliday, 2010). At some archeological sites, Clovis artifacts occur immediately below the YD basal horizon but are absent above (Haynes, 2008). Other paleoenvironmental changes during the terminal Pleistocene include regional shifts in vegetation, fire frequency, and landscape-scale geomorphic response (e.g., Peros et al., 2008; Marlon et al., 2009; Pinter et al., 2011). Intense scientific interest, research, and discussion have long focused on these changes. In particular, the timing of post-LGM climatic changes, human arrival in North America, and megafaunal extinctions – and the question of which event(s) caused the other(s) – have engendered particularly vigorous debate (e.g., Grayson and Meltzer, 2003 + comments and reply). Against this background, the YDIH introduced a grand, potentially unifying solution promising to tie together some or all of these post-LGM changes.

Although the YDIH was formally debuted in 2007, a version of the hypothesis first appeared in Firestone and Topping (2001), with substantial elaboration in the Firestone, West, and Warwick-Smith (2006) book. These early sources contain a number of suggestions – impact origin of glacial drumlins, supernova eruptions leading to "deadly nerve toxins" in Pleistocene algal mats, etc. – that are highly unlikely. Morrison (2010) suggested that "If more scientists and science journalists had been aware of [Firestone et al. (2006)] when the YD hypothesis was first published in PNAS, it might never have gained traction." But it may be unfair to judge later versions of the YD hypothesis based on the excesses of its early iterations.

The second phase of the YD impact hypothesis emerged with the addition of a number of collaborators, culminating in the dedicated session and press conference at the 2007 AGU meeting. Details of the YD hypothesis at this stage were codified in Firestone et al. (2007a) and in Kennett et al. (2008, 2009a,b). These authors propose a cometary impactor (4.6 km in diameter in Firestone, 2009) that either struck or exploded over the Great Lakes region, destabilizing the Laurentide ice sheet, releasing volumes of meltwater that caused the YD reglaciation, ignited hemisphere-spanning wildfires, killed the North American megafauna and the coeval Paleoindian population, etc. (Firestone et al., 2007a). Firestone et al. (2007a) reported extraterrestrial and impact-related signatures from 10 sites with deposits dating to, or presumed to date to, the Bølling–Allerød-to–YD transition (or "Younger Dryas Boundary" = YDB) at about 12,900 cal BP. Nine of the sites were located in North America, and one site was located in Belgium. Results were also presented from "in and around" 15 Carolina Bays in the southeast USA (see discussion below).

Worldwide and through geological time, ~180 impact structures have been rigorously documented (Grieve and Therriault, 2004; for current listing see Earth Impact Database: http://www.unb.ca/passc/ImpactDatabase/), and ~3–5 new impact structures are recognized each year (e.g., Grieve, 1997). The recognition of geological structures and ejecta layers on Earth as being of impact origin requires the detection of either shock metamorphic effects in minerals and rocks, and/or the presence of a meteoritic component in these rocks (see the reviews in, e.g., Stöffler and Langenhorst, 1994; Koeberl, 2007; French and Koeberl, 2010). As yet, no geological structure dating to the onset of the YD has been identified, nor have any of the traditional impact markers (see Discussion). Despite lack of evidence of a YD impact structure, Firestone et al. (2010) suggested "Four holes in the Great Lakes, some deeper than Death Valley, are proposed as possible craters." Other proponents of the YD impact suggest that the lack of an impact site and the lack of traditional impact markers result from either: a) the impact occurring on the ice sheet and leaving little preserved evidence; or b) a fragmented meteoroid or cometary bolide, or fragments thereof, that detonated in the atmosphere (but see below for discussion). Although not impossible (Napier, 2010), these scenarios so far lack physical evidence.

According to its proponents, one of the main strengths of the YDB impact hypothesis, has been the broad range of extra-terrestrial (ET) evidence found in common association at this time horizon. Among the signatures reported at the YDB are: (i) entrance "wounds"/particle tracks in archeological chert, (ii) magnetic nodules in Pleistocene tusk and bone, (iii) fullerenes, (iv) ^{3}He, (v) elevated iridium concentrations, (vi) radioactivity peaks, (vii) orientation and origins of the Carolina Bays, (viii) carbon spherules and glass-like carbon, (ix) concentrations of magnetic grains, (x) magnetic microspherules, (xi) charcoal and soot and other byproducts of intense wildfire, and (xii) nanodiamonds (Firestone et al., 2007a; Firestone, 2009). The purpose of this paper is to review the YD impact hypothesis, including how that hypothesis has evolved over time, assess the evidence that has been proposed, and present new results testing the YDIH. For each of the major lines of YD evidence originally proposed, subsequent analyses could have led to one of three possible outcomes:

Outcome 1 the original observations and their interpretations reproduced, confirming the impact origin of that evidence.
Outcome 2 the original observations themselves reproduced but not their interpretation; those interpretations instead being consistent with alternative mechanisms other than a YD impact.
Outcome 3 the original results proven to be non-reproducible, self-contradictory, or physically impossible.

After three years of independent research focused on testing the 12 lines of purported evidence of a YD impact, a broad assessment of that evidence is now possible.

2. Early YDB impact markers

Several signatures of purported extraterrestrial origin were reported in early publications, generally up to and including Firestone et al. (2007a), but subsequently faded out of most YD discussions. For the sake of clarify and fairness, these signatures should be discussed first and separated from others that have remained in more widespread recent discussions. These early YDB markers included: (i) chondrules embedded in archeological chert fragments, and (ii) metallic micrometeorites or meteoritic fragments embedded in mammoth tusks and other Pleistocene faunal remains. Other purported signatures also were reported in early YDB publications, but later publications are split, with some proponents still standing behind the validity of these markers, and others seeming to back away. These purported signatures include: (iii and iv) fullerenes enriched with extraterrestrial helium (^{3}He), (v) anomalous iridium abundances, (vi) peaks in radioactivity in YDB horizons, and (vii) the nature and content of the Carolina Bays.

2.1. Micrometeorite particles and/or tracks in archeological chert

The first evidence of a YD impact was the report of archeological material from the Great Lakes region with "a high density of entrance wounds and [micro-meteorite] particles at depths" (Firestone and Topping, 2001). These meteoritic particles (reported as chondrules; i.e., constituents of chondritic meteorites) purportedly had penetrated chert flakes exposed at the ground surface at YD time. These "entrance wounds" reportedly were measured at high angles to the ground surface (more vertical) near the proposed impact site near the Great Lakes, and at lower angles at progressively greater distances away (Firestone et al., 2006). No other researcher group has confirmed either the purported chondrule particles or their associated chert entrance wounds, and most of the recent YD publications have abandoned this line of evidence.

Chondrules and micrometeorites are rather fragile objects that are unlikely to survive impact into a hard surface. Furthermore, micrometeorites are well known to decelerate in the atmosphere so that they descend to the surface like other dust grains (e.g., Love and Brownlee, 1993) and would not have sufficient velocity to penetrate hard surfaces. Using the three outcomes outlined above, and given problems with the physical plausibility, this proposed evidence must be regarded in the third group — i.e., unsubstantiated results.

2.2. Magnetic fragments in tusk and bone material

Firestone et al. (2006) also emphasized the discovery of macroscopic magnetic particles embedded in mammoth tusks and other Pleistocene megafaunal remains. The initial claim was that these metallic particles represented meteorite fragments ("cosmic bullets") derived from the YD impactor and directly linking the proposed impact event with the megafaunal demise. The same problems as to the source and physical implantation mechanism of such particles arise as for the ET chondrules discussed in the previous section. Subsequent age dating revealed that the tusks and bone material in question did not date to 12,900 BP, but rather to a range of earlier ages more-or-less centered on 33,000 BP (Firestone et al., 2007b; Hagstrum et al., 2010), leading the authors to invoke another ET atmospheric airburst event ~20,000 years prior to the YD. (One perforated bison skull dated at 26,000 BP was interpreted as "exposure of the bison to an enriched source of radiocarbon following the impact" [Firestone et al., 2007b]). To date no rigorous reanalysis of these iron concentrations has been published, but alternative explanations may include diagenetic alteration or nodular accumulation of iron in the Pleistocene bone and tusk. In either case, this line of evidence has become moot with regard to the YD impact hypothesis itself, given the proponents' new dating of that material.

2.3. Fullerenes and ET helium

Another type of evidence initially cited as an extraterrestrial signature in YDB deposits was the presence of fullerenes (carbon allotropes in the form of spheres and other closed structures). These fullerenes purportedly contained trapped He enriched in ^{3}He relative to terrestrial He isotopic compositions (Becker et al., 2007; Firestone et al., 2007a). However, isolation of fullerenes with isotopically anomalous trapped gasses has never been replicated, and the original study has been criticized for a number of years for methodological shortcomings and non-reproducible results (Farley and Mukhopadhyay, 2001; Isozaki, 2001; Buseck, 2002; Farley et al., 2005). Although fullerenes are present in some classes of meteorites, claims of fullerenes isolated from stratigraphic impact horizons have been repeatedly challenged (e.g., Taylor and Abdul-Sada, 2000; Braun et al., 2001; Buseck, 2002). Furthermore, combustion products can contain fullerenes, e.g., they have been identified in candle soot (Aldersey-Williams, 1997) and can form in terrestrial wildfires (Heymann et al., 1996). Although some more recent YD publications continue to present fullerenes and ^{3}He as supporting evidence (Firestone, 2009; Firestone et al., 2010), these markers are not mentioned in other recent papers (e.g., Kennett et al., 2009a,b). In terms of the three potential outcomes above, both the fullerene and ^{3}He results must be regarded, at best, as unsubstantiated (Outcome #3).

2.4. Iridium

Siderophile elements, especially the platinum group elements (PGE), are significantly more abundant in meteorites than terrestrial upper crustal rocks. Their presence in sediments is one line of evidence unanimously accepted by impact researchers. Often Ir concentration is measured as a proxy for all PGEs, because it can be measured with the best detection limit of all PGEs by neutron activation analysis. Taken out of context (i.e., without other geochemical and petrographic data), however, small Ir anomalies alone have little diagnostic power (see detailed explanations in Koeberl, 1998, 2007; French and Koeberl, 2010). Alternatively, the presence of an extraterrestrial component can be detected through measurement of Os and or Cr isotopic abundances (e.g., Koeberl, 2007; Koeberl et al., 2007).

Firestone et al. (2007a) presented Ir concentrations in samples dating to 12,900 years BP as high as 117 ppb, a value higher than at most Cretaceous–Tertiary (K–T) boundary sites or for impact melt rocks of confirmed impact craters (e.g., Koeberl, 1998, 2007). Subsequent examination of these results, however, showed that the reported YDB Ir concentrations are not directly comparable to K–T values or those of other impact horizons. The 117 ppb value, for example, and another of 51 ppb Ir, were not bulk sediment concentrations at all, but rather were measured from lab separates of microspherules and magnetic grains (see discussion below). These magnetic sub-samples were 0.3–17 g/kg of the bulk samples from which they were collected (Firestone et al., 2007a), equivalent to a potential concentration factor of 59 to >3000 times for any component present in the magnetic grains at higher levels than the overall bulk samples. Firestone et al.'s (2007a) bulk concentrations of Ir were below their detection limit of 0.5–1.0 ppb at six of ten sites. The remaining four sites had maximum concentrations of 2.3–3.8 ppb Ir, values that the authors noted are anomalously low, requiring them to invoke an Ir-depleted impactor.

More recently, independent analyses (Paquay et al., 2009; Koeberl, 2010-unpublished data on samples provided by D. Kennett) failed to replicate initial claims for any elevated Ir levels. Samples splits were provided by A. West to P. Claeys and showed "no Ir or PGE … no meteoritic component whatsoever" … down to detection limits "in the 10 ppt range" (P. Claeys, pers. comm.). These splits were from "the exact same samples as listed in Firestone et al., 2007a,b" using "large samples to avoid any nugget effect" (P. Claeys, pers. comm.; Paquay et al., 2009). Other platinum group elements also showed no significant ET input in YDB-age samples (Paquay et al., 2009). Similarly, side-by-side analyses at the Murray Springs type locality ("Where they [Firestone et al.] collected, we collected;" Haynes et al., 2010), failed to reproduce any consistent Ir peak within the section, with the highest single Ir value occurring in modern alluvium at the site (Haynes et al., 2010). Failure to reproduce even the modest bulk iridium concentrations initially reported in YDB-age deposits, including in side-by-side and identical sample splits, poses unanswered questions about these discrepancies.

2.5. Radioactivity peaks

Firestone et al. (2007a) reported that "Some megafaunal bones in the YDB are highly radioactive relative to other stratigraphic intervals, … [and] high concentrations of U and Th were found in the YDB sediment at six of six Clovis-age sites analyzed and in four of four [Carolina] Bays". Firestone (2009) elaborated: "the upper surfaces of mammoth fossils, which were directly covered by the black mat, were strongly magnetic and radioactive" with no "excess radioactivity [on] the lower surfaces of those same fossils". The "black mat" identified above refers to a dark-colored, fine-grained layer that has been identified at a number of Clovis archeological sites across North America (Haynes, 2008), including the black-mat type locality at Murray Springs, Arizona, and recently one site in South America (Mahaney et al., 2010). The nature and interpretation of these dark layers are discussed at length later in this paper. Haynes et al. (2010) report radioactivity measurements from the same sections as measured by Firestone and colleagues: at Murray Springs and at two other Clovis sites, but were unable to reproduce the results reported by Firestone et al. (2007a). The tops of the occupation surfaces at the two other Clovis sites show radiation counts very slightly above other horizons, whereas the YDB layer and black mat at Murray Springs show no radioactivity peaks at all. Haynes et al. (2010) attribute the modest scatter in radioactivity levels in these sections to "variations in detrital radioactive minerals such as allanite or monzanite". At any rate, radioactivity of any sort is not related to impact processes or events (no enhanced levels of radioactivity are known from any recent impact structures, nor is there any physical reason why there should be such a connection).

2.6. Carolina Bays

Another element of the YDIH highlighted in several sources (Firestone and Topper, 2001; Firestone et al., 2006, 2007a,b; Firestone, 2009) is the Carolina Bays. The Carolina Bays include thousands of circular to elliptical depressions across the coastal plain of the southeastern USA. Origin of the Carolina Bays was debated for many years, with some notably odd mechanisms proposed (e.g., "gyroscopic forces," Cooke, 1945; spawning fish, Grant, 1945). Melton and Schriever (1933) attributed the Bays to a swarm of oblique impact strikes. In contrast, more recent research has focused on geomorphic origins. YDB proponents returned to the impact mechanism for the Bays, based on their elliptical forms, parallel alignment, and purported YD impact markers collected from the bay rims and interiors (Howard et al., 2007; Kobres et al., 2007; Firestone, 2009). Firestone et al. (2006) implied that the Carolina Bays formed from impacts of large-scale secondary ejecta from the primary impact site, whereas Firestone (2009) suggested "a high-temperature shock wave … that [raced] across the continent creating the impact debris-rich Carolina Bays as it passed."

Research both before and since the YDIH suggests that an impact origin for the Carolina Bays is unlikely. No meteoritic material has ever been recovered from the bays (claims reviewed here excepted). Furthermore, the axes of the elliptical bays do not truly "converge near the Great Lakes [the proposed impact/airburst site]" (Howard et al., 2007; Firestone, 2009), but rather vary in orientation both locally and regionally (Johnson, 1942; Thom, 1970). Furthermore, the Carolina Bays did not form instantaneously, but rather over significant time. Recent independent dating shows "multiple periods of bay-rim accretion with intervening intervals of erosion" (Grant et al., 1998; Ivester et al., 2003; Ivester et al., 2007). Most recently, 22 new ^{14}C dates of various carbon forms collected from the Carolina Bays by Firestone (2009) yielded ages ranging from a maximum of 6565 ± 15 BP to the present, further forward to 755 ± 15 BP in the future. Firestone (2009) suggests that all 22 samples actually formed at 12,900 BP, but that "the impacting object was ejected by a recent near-Earth supernova in which case carbon [was] enriched in ^{14}C by [a factor of] 10^7". Perplexing explanations aside, these dates seem to confirm suspicions that Firestone's samples from the Carolina Bays lack stratigraphic context and may incorporate significant modern materials (carbon dating to or after atmospheric nuclear testing will yield negative ^{14}C dates).

2.7. Summary of the lines of evidence above

Some elements of the YDIH merit further discussion and perhaps additional research, but the lines of evidence reviewed above – particle/cosmic-ray trackways, iron "bullets," radiation peaks, fullerenes, ^3He, iridium, and the suggested impact origin of the Carolina Bays – invite a clear judgment. Of the evidence reviewed above, none has been independently reproduced or substantiated, and none of the existing results and interpretations meet the minimum threshold for scientific credibility. Shedding the most marginal elements of the YD impact story should help clarify further discussion of the hypothesis.

3. Remaining YDB "impact markers"

At the present time, four classes of YD impact-related evidence remain, or recently have remained, in widespread discussion: (viii) reports of carbon-rich grains, i.e., "carbon spherules," "carbon elongates," and "glass-like carbon" in YDB deposits; (ix and x) concentrations of magnetic grains and microspherules in YDB deposits; (xi) material purportedly resulting from impact ignition of continental wildfire; and (xii) nanodiamonds in YDB carbon grains.

3.1. Carbon spherules, carbon elongates, and glass-like carbon

Several carbonaceous forms have been identified and cited as impact-related markers in YDB deposits. Firestone et al. (2007a) reported concentrations of "carbon spherules" and "glass-like carbon" in the horizons of supposed YDB age at the various Clovis, Carolina Bay, and other sites they sampled. Carbon spherules are reported as "highly vesicular, subspherical-to-spherical objects," 0.15–2.5 mm in diameter, with "cracked and patterned surfaces, a thin rind, and honeycombed (spongy) interiors" (Firestone et al., 2007a). These spherules were reported at concentrations of up to 1458/kg (max. value in sediments from the Carolina Bays). Also reported was so-called glass-like carbon at concentrations of 0.01–16 g/kg, consisting of angular fragments up to several cm in size, with a glassy texture "suggest[ing] melting during formation" (Firestone et al., 2007a). According to Firestone (2009), "[g]lass-like carbon doesn't exist naturally and the man-made varieties are shown to have a structure similar to Fullerenes." Most recently, Kennett et al. (2008) identified a third carbonaceous form in YDB deposits, which they named "carbon elongates." Carbon elongates are reported as more ellipsoidal in shape that the carbon spherules, and with a different internal structure — a difference characterized by Kennett et al. (2008) as "a much coarser interior cellular structure" and by Kennett et al. (2009b) as "an irregular array of walls and voids [in contrast with] a well-organized honeycomb (reticulated) pattern" in the spherules.

Kennett et al. (2008, 2009b) report that carbon spherules were found in, and only in, the basal layer of their Arlington Canyon type-section — i.e., in their inferred YDB unit. In contrast, their reported carbon elongates are concentrated in that same basal unit but also occur throughout that section. Firestone et al. (2007a,b) report "glass-like carbon" concentrated in their YDB horizon but also present in the overlying black mat unit. Firestone and colleagues also report both carbon spherules and glass-like carbon associated with modern forest fires that they sampled. Although Firestone et al. (2006) initially implied that carbon in these carbonaceous forms was extraterrestrial in origin, subsequent identification of similar materials in modern samples has shifted these interpretations. Indeed, no such materials have even been found to be associated with known impact deposits (French and Koeberl, 2010). Most YD impact proponents now assert that carbon spherules, carbon elongates, and glass-like carbon result from intense wildfire ignited by the purported impact event — "intense fires … ignited by an intense radiation flux associated with a cosmic impact" (Kennett et al., 2009b; see fire discussion below). The impact-related ignition of these fires is documented, reportedly, by the coincident timing at multiple sites and by the pervasive presence of ET components, in particular nanodiamonds, within the YDB carbon.

3.1.1. Recent assessment of carbon forms

Scott et al. (2010) found that the carbonaceous spherules and elongates associated with the YDB have a biological explanation rather than a cometary/meteoritic source or impact-related ignition of intense wildfires. Instead, the carbonaceous spherules and elongate forms are indistinguishable from fungal sclerotia and/or arthropod coprolites. Sclerotia (Townsend and Willetts, 1954; Willetts, 1969; Chet, 1975) occur commonly on a wide variety of plants and in soil (Farr et al., 1989; Watanabe et al., 2007; Fig. 1a and b). Sclerotia are small spherular objects that have internal structures identical to those reported in sections of YDB spheres (Scott et al., 2010). Scott et al. (2010) found abundant sclerotia in deposits ranging in age from ~20,000 cal BP through the latest Pleistocene and Holocene, including from modern wildfire sites exposed to low-temperature surface fires. The elongate carbon spherular forms also may be fungal in origin (Scott et al., 2010), although some or all of these elongates may represent arthropod (insect and termite) fecal pellets (coprolites; Adams, 1984; Collinson, 1990; Scott, 1992; Fig. 1c). Kennett et al. (2009a) reported that the "shape of elongates ranges from angular (hexagonal in cross-section) to subrounded." Elongates with hexagonal cross sections are almost certainly termite coprolites (Adams, 1984; Collinson, 1990; Scott, 1992). Without full documentation of the elongate specimens used by Kennett et al. (2008, 2009a,b), it is not yet possible to definitively dismiss claims of a new elongate particle type, but both carbon spherules and "carbon elongates" have ubiquitous terrestrial parallels that fully explain all observations presented to date. Furthermore, analyses of fossil carbon spherules as well as experimental charring of modern fungal sclerotia contradict claims that the YD spherules originated in intense, impact-triggered wildfire; these experimental results are reviewed in the section on fire below.

The reported glassy carbon has several possible origins, none of which imply high temperatures. Some of it may represent solidified tars from low-temperature charcoalification (Scott, 2010). Vitrified charcoal forms have previously be considered to be formed by high temperatures, but recent studies suggest that they are formed at relatively low temperatures (McParland et al., 2010) and again may represent the precipitation of tars within the wood matrix. Firestone and colleagues neither provided detailed compositions or descriptions of these materials, nor did they provide explanation why such materials should be related to hot fires.

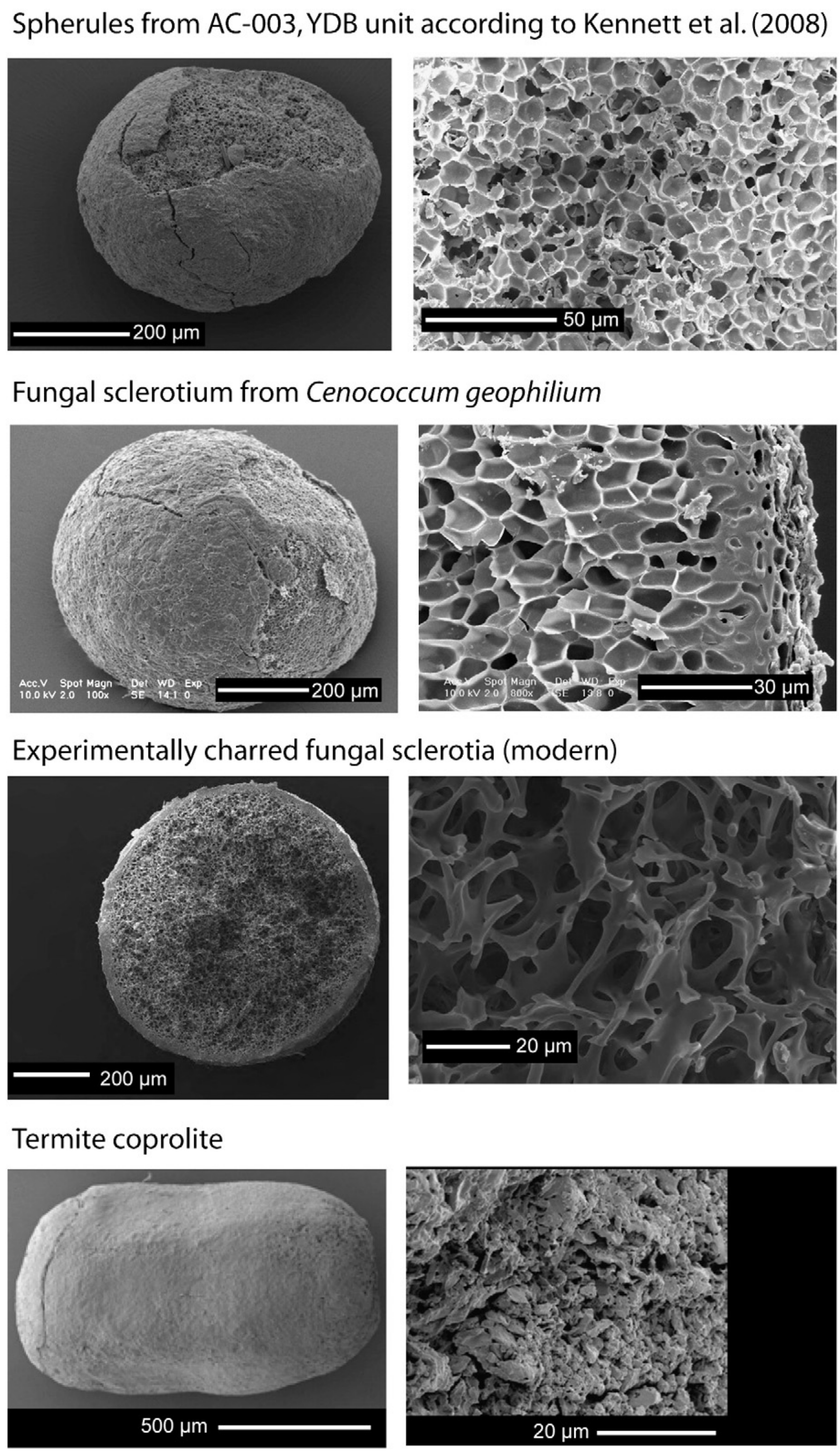

Fig. 1. Carbonaceous spherules from purported YDB deposits are indistinguishable from fungal sclerotia in deposits of a wide variety of ages up to modern. "Carbon elongates" reported by Kennett et al. (2008) appear to be termite and/or arthropod coprolites and/or elongate forms of sclerotia. Many additional illustrations and detailed discussion are in Scott et al. (2010).

3.2. Magnetic grains and spherules

Firestone et al. (2006, 2007a) reported finding enhanced concentrations of magnetic grains and magnetic microspherules in inferred YDB-age deposits at most of their sites across North America and Europe. Magnetic grains were collected from bulk sediment at concentrations averaging 3.4 g/kg and were described as "measuring 1–500 μm, irregularly shaped and often subrounded" (Firestone et al., 2007a). Concentrations of these grains were reported to peak in the inferred YDB layer at all 25 sites studied. A subset of the magnetic grains were termed "magnetic microspherules," which were described as highly spherical magnetic grains, 10–100 μm in diameter. These spherules were identified by "scann[ing] microscopically" "one or more ~100 mg aliquots [units] of the magnetic fraction" (Firestone et al., 2007a). Firestone et al. (2007a,b) note that "magnetic grains and microspherules are anomalously enriched in Ir and Ti … and are enriched in water (up to 28 at.%), especially at northern sites." Firestone (2009) adds that "The water appears to have been trapped inside the magnetic grains since they often explode when placed in a microwave oven…. 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." Concentrations of both magnetic grains and magnetic spherules reportedly peak in the YDB layer, with layers above and below purportedly containing zero or near-zero concentrations (Firestone et al., 2007a; Firestone, 2009). Spherules are reported at concentrations of up to 2144 spherules/kg at 13 of 14 sites where samples were tested for spherules.

Beginning in 2007–08, several research groups, including our own, set out to quantify magnetic/metallic spherule concentrations in latest Pleistocene sequences. To date, results have been published by Surovell et al. (2009) and by Haynes et al. (2010); new results are also presented here (see below). Surovell et al. (2009) duplicated separation and counting techniques outlined in Firestone et al. (2007a) and in supplementary protocols provided by YDIH co-author A. West (Surovell et al., 2009, Supporting Information). Surovell and colleagues tested seven sites across North America, finding magnetic grains and spherules throughout all seven sequences, but with no defined peak at 12,900 BP at any of those sites. Firestone (2009) responded that Surovell et al. missed the true YD horizon, a layer characterized in that 2009 paper as "only a few mm thick." Previously Firestone et al. (2007a) described the YD layer as having an "average thickness of 3 cm," and Kennett et al. (2008) reported 15 ^{14}C dates all indistinguishable from 12,900 cal BP through 4+ m of their study section in California. (If this trend in the YD layer thickness were to continue – from meters to cm to mm *to zero* – then YD proponents and skeptics would find themselves in agreement.) Haynes et al. (2010) identified magnetic grains and spherules from both YDB-age and modern samples and concluded that the distribution of those materials in sediment samples "can be explained by the fluvial dynamics affecting these sediments."

3.2.1. Additional results

Our own research group has completed spherule frequency analyses complementary to the work by Surovell et al. (2009). Rather than targeting horizons of YDB-age at sites across North America, we dated and sampled multiple latest Pleistocene "black mat"-like strata in several sections in the Northern Channel Islands of California, the same area on which Kennett et al. (2008, 2009a) focused. Fluvial fill sequences (Fig. 2) on these islands contain near-continuous stratigraphy from the LGM up to the late Holocene, including multiple dark colored strata, each of which resembles the YD "black mat" layer. In our sections, these dark horizons represent fine-grained, marginal floodplain facies with incipient to moderate paleosol development. We hypothesized that these horizons, along with the YD black mat, were likely settings for accumulating spherules in the form of micrometeorite ablation fallout. In Sauces Canyon on Santa Cruz Island, and in Verde Canyon and selected other sites on Santa Rosa Island, we measured and dated the stratigraphy and collected sediment for separation of magnetic grains and spherules from the dark, fine-grained strata and from selected lighter-colored, coarse-grained strata.

We followed the protocols outlined in Firestone et al. (2007a) for separation and sampling magnetic grains (as described above). In addition, we also separated metallic spherules from bulk sediment using a density-based separations using heavy liquids (sodium polytungstate; $\rho = 2.8–2.9$ g/cm^3) and centrifuge separation. These additional density-based analyses tested whether Firestone's use of a neodymium magnet for separation may have captured mineral grains that are only weakly magnetic. For both approaches, final identification of candidate spherules from the magnetic and density-based separates was done using reflected-light microscopy, selecting all grains in the correct size fraction (10–100 µm) that were highly spherical, with smooth and polished surfaces (initially identifiable under reflected light by a sharp, circular reflection from the apex of the grain). Selected spherical grains thus identified were analyzed for composition and mineralogy using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), micro X-ray diffraction (XRD), and Raman spectroscopy.

Our analyses of the latest Pleistocene sections in California confirm and complement the findings of Surovell and colleagues. Spherules, as previously defined, were present in almost all layers analyzed, equaling or substantially exceeding the concentrations reported by Firestone et al. (2007a). In the Sauces section (Fig. 3), duplication of the Firestone separation technique yielded magnetic grains in all units sampled, at concentrations ranging from 24.9–99.0 g/kg of bulk sediment. Spherules were also present in all of these units as well, at concentrations from 2 to 5/g of bulk sediment. The Verde Canyon section on Santa Rosa Island (Fig. 4) yielded similar results, with 50.6–101.3 g/kg magnetic grains and 2–4 spherules/g for samples duplicating separation technique published in Firestone et al. (2007a). Two additional samples from Arlington Canyon on Santa Rosa Island (Figs. 3–4) also yielded similar results, with 99.9–164.5 g/kg magnetic grains and 2–3 spherules/g of bulk sediment.[1] Our density-based separations yielded similar concentrations of spherular grains (present in all samples, at 1–6/g of sample), but generally lower concentrations of grains within the targeted density range (4.9–5.2 g/cm^3) than the concentration of magnetic grains.

No clear YDB "marker bed" was present in any of our sections, so unlike Firestone and Surovell, our results focus on the distribution (and nature; see below) of spherules through sediments pre-dating, dating to, and post-dating the onset of the YD. Looking first at magnetic grains, all of our concentrations derived from the duplicate separation technique (lowest = 24.9 g/kg) exceeded all of Firestone's (2007a) concentrations (highest = 17.10 g/kg). We strongly concur with Haynes et al. (2010) that magnetic grains in different sedimentary sections and strata clearly depend primarily upon the abundance of magnetite and other common (i.e., terrestrial) magnetic minerals in the corresponding source rocks, combined with sorting and differential weathering processes active during sediment transport and deposition. In addition, all of our samples contained spherules, and all but one sample had spherule concentrations exceeding all but two of Firestone's (2007a) reported concentrations (1020 and 2144/kg = 1.02 and 2.144/g). Most of Firestone's concentrations fell in the range, 20–800 spherules/kg, or 0.02–0.8/g (i.e., 8 spherules per 100 mg sample "aliquot", down to 1/5th of a spherule per sample [?]).

The spherule counts presented here show spherules present at or above the peak concentrations reported by Firestone et al. (2007a) in multiple horizons dating from the late Pleistocene into the Holocene. All of the results here are consistent with the findings of Surovell et al. (2009) and Haynes et al. (2010) that magnetic/metallic spherules are not limited to, nor even concentrated in, YDB deposits. Furthermore the results here also confirm that concentrations of magnetic grains seem to be controlled by detrital input. Indeed, such magnetic grains are a normal and expected component of almost any terrestrial sediment sample.

3.3. Wildfire combustion products (fire evidence)

A central feature of the YD impact hypothesis has been the suggestion of intense, impact-ignited wildfire that ranged from coastal California, across North America, to Europe. Evidence cited for these hemisphere-spanning fires includes "charcoal, soot, carbon spherules, and glass-like carbon, all of which suggest intense wildfires" (Firestone et al., 2007a). Soot was reported at a few of the YDB

[1] Note that spherule counts per gram of sample = spherules/kg. Apparent differences in precision (e.g., 5 g^{-1} in our counts vs. 2.144 g^{-1} from Firestone) are a rounding artifact resulting from Firestone et al.'s sampling unit (100 mg units of the magnetic fraction normalized to kg^{-1} of bulk sediment; Firestone et al., 2007a).

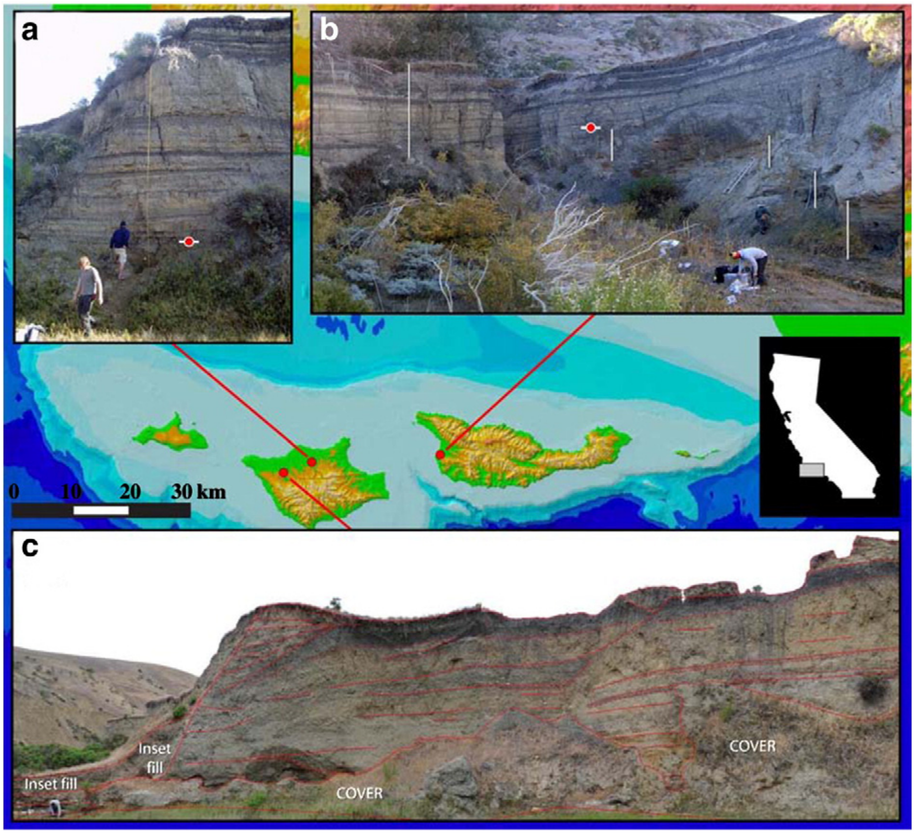

Fig. 2. Latest Pleistocene to Holocene stratigraphic sections in the Northern Channel Islands of California, including in Verde Canyon, Santa Rosa Island (a); Sauces Canyon, Santa Cruz Island (b); and Middle Arlington Canyon on Santa Rosa Island (c). Section (c) is identical or closely proximal to the location reported by Kennett (2008, 2009a,b). Firestone et al. (2007a) also report YDB impact markers from Daisy Cave on San Miguel Island, the smaller island visible immediately to the west.

sites (Firestone et al., 2007a; Kennett et al., 2009a,b), although this claim cannot be confirmed from information presented to date. In addition, Firestone et al. (2007a) reported that "[h]igh-temperature PAHs … are present in the YDB, but not above or below it at each of three sites analyzed (Daisy Cave, Murray Springs, and Blackwater Draw), suggesting that intense fires occurred at these locations." PAHs, or polycyclic aromatic hydrocarbons, have been associated with vegetation burning and/or hydrocarbon emissions at the K–T boundary (Belcher et al., 2009). Neither Firestone et al. (2007a) nor subsequent YD publications to date have presented necessary details to fully evaluate the original claims regarding PAHs, however we note that the presence of PAHs, like soot, do not require high-intensity fire, but rather just the presence of combustion of some kind (Simoneit, 2002; Marynowski and Simoneit, 2009; Scott, 2010; Scott et al., 2010).

Greenland ice-core data show increased ammonium and nitrate levels at the YD onset (Mayewski et al., 1993, 1997), which Firestone et al. (2007) have suggested as a further signature of intense and widespread biomass burning. Melott et al. (2010) argued that biomass burning across the North America would be sufficient to explain the YD ice core data, but peaks in nitrate and ammonium are also observed in ice cores at the time of the Tunguska event where the area burned was insufficient to account for the ice core data. Higher-resolution data, further analysis, and assessment of a broader range of mechanisms are required before this evidence can be adequately evaluated.

To date, assertions of a catastrophic, YDB-age "mega-fire" have not been corroborated by independent fire records. Marlon et al. (2009) examined archives of dated charcoal records across North America and found that no single regional fire event is present. Analyses of geologic and paleo-ecological records in Europe have also concluded that there is no evidence of a regional YD-age, high-intensity fire (van der Hammen and van Geel, 2008; Kaiser et al., 2009). In addition, we present (below) detailed charcoal analyses from some of the same areas at which catastrophic impact-driven fire events were reported in the YD literature (e.g., Kennett et al., 2008). These sections document fire before, during, and after 12,900 cal BP, with no evidence of high-intensity conflagration at the YDB itself.

The fixation of the YD impact hypothesis on continental-scale fire seems to stem from the origins of the hypothesis in the "black mat" first reported by Haynes (1984, 1991, 2007, 2008). Haynes reported this dark-colored stratum at a number of Clovis-age sites across North America. The layer was consistently dated near the onset of the YD, separating Clovis archeological material and megafaunal fossil remains below the black mat, and none above. Firestone and colleagues asserted that the black mat layer consists of "widespread peaks of charcoal in or near the YDB" (Firestone et al., 2007a) and interpreted the layer as "formed from the ashes of the impact" (Firestone, 2009). In reality, no such charcoal peaks and no ash are present.

Dark color notwithstanding, the YD black mat deposits do not represent a paleo-fire horizon, and these deposits contain little or no fire byproducts. Haynes et al. (2010) state that the Murray Springs black mat sample cited by Kennett et al. (2008) did not contain "charcoal, vitreous carbon, or vitrinite;" and furthermore that most of "hundreds of black mat samples" contained zero detectable charcoal. Our group also collected material from the Murray Springs black layer and tested its organic content for total organic content (TOC) analysis and by hydrofluoric acid (HF) digestion. TOC in the mat deposit itself was 14.92 wt.%, substantially less than in the sand above. The HF digestion of the mat deposit yielded zero macroscopic charcoal or other organic particles (>180 μm) and only trace amounts of microscopic (<180 μm) organics. Soot and polyaromatic hydrocarbons reported by Firestone et al. (2007a) – if these results can be reproduced – are explained by Haynes et al. (2010) as proximity of the Firestone sampling site to a Clovis-age hearth at that horizon.

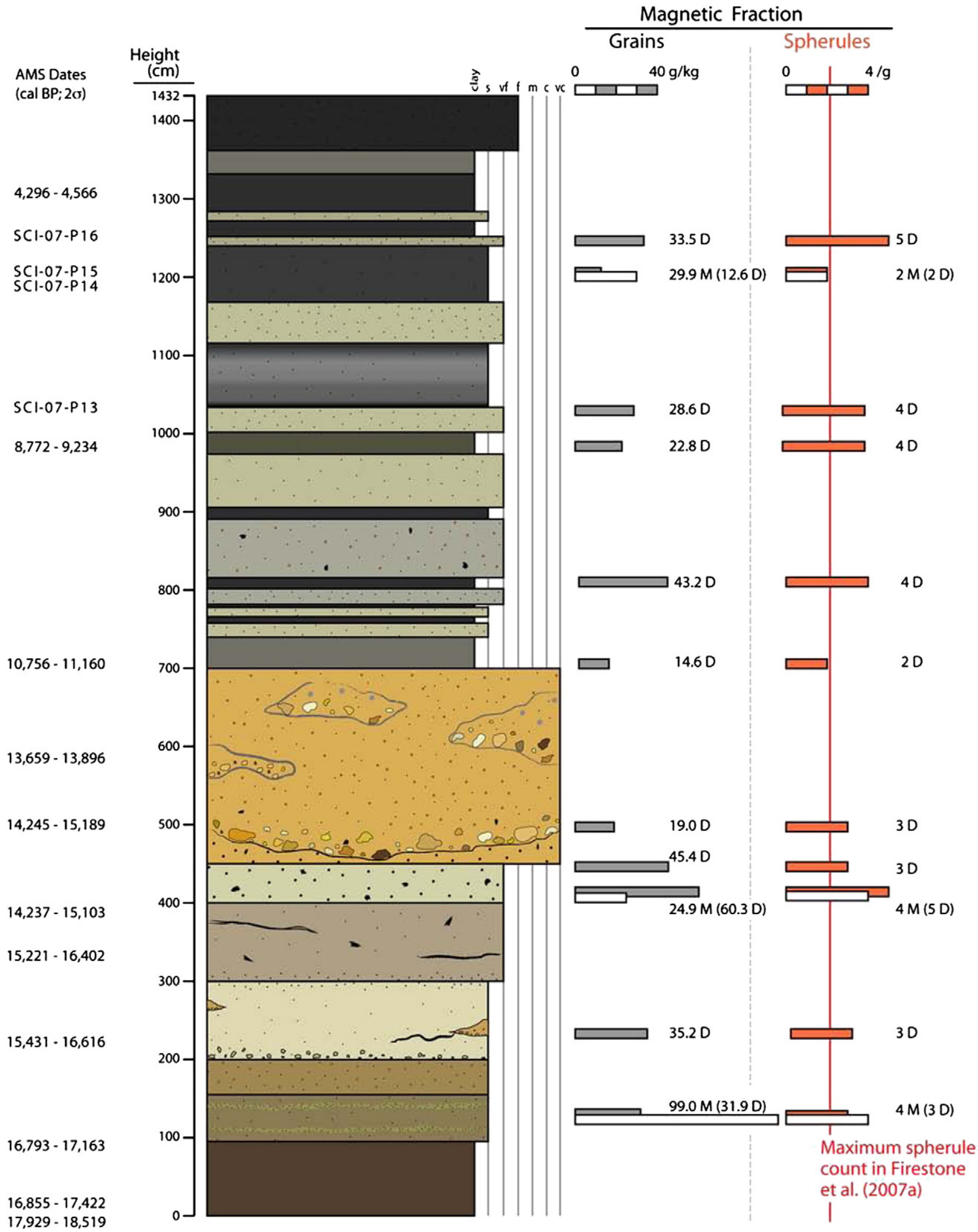

Fig. 3. Stratigraphic section and concentrations of magnetic grains and spherules from the Sauces Canyon section, Santa Cruz Island, CA. Results are given for both magnetic separations (following Firestone et al., 2007a; "M") and for density--based separations ("M").

Previous research on "the black mat" and similar deposits elsewhere concluded that these deposits originated as paleo-wetland deposits and/or wetland paleosols. Although expressed as a single dominant dark layer at several sites (Haynes, 2008), equivalent dark and fine-grained deposits occur in multiple units in many arid to sub-humid locations worldwide, dating from the late Pleistocene to the present (e.g., Quade et al., 1998; Rech et al., 2003; Mandel, 2008). Holliday and Meltzer (2010) note that at black-mat sites across North America, including Murray Springs, these units are time-transgressive horizons that pre-date, post-date, and broadly span the start of the Younger Dryas. Claimed "black mat" sites

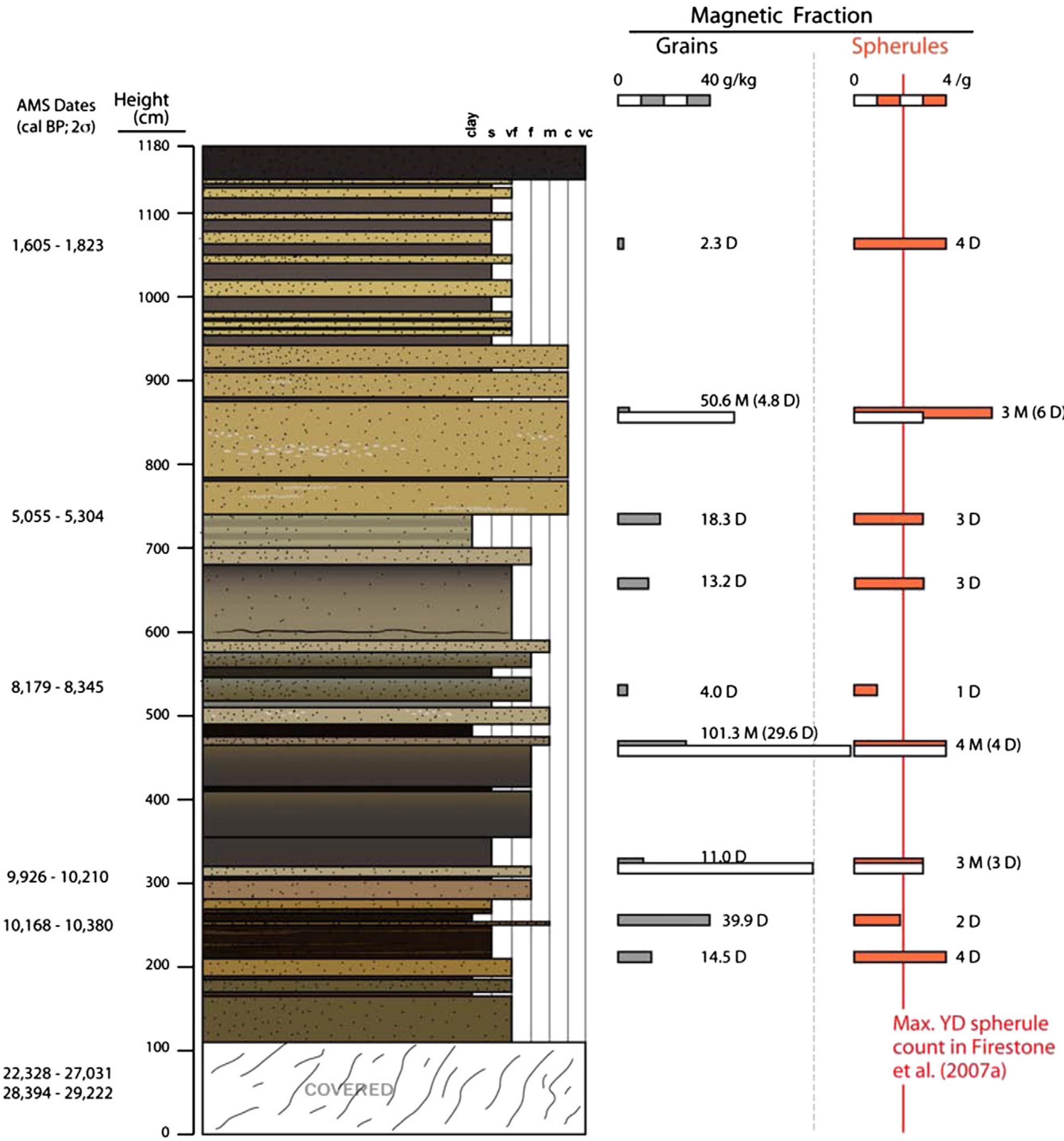

Fig. 4. Stratigraphic section and concentrations of magnetic grains and spherules from the Verde Canyon section, Santa Rosa Island, CA. Results are given for both magnetic separations (following Firestone et al., 2007a; "M") and for density-based separations ("M").

in Europe are actually eolian sands with scattered wildfire charcoal for which any impact origin has been vigorously disputed (Latałowa and Borówka, 2006; van der Hammen and van Geel, 2008; Kaiser et al., 2009). A purported "black mat" in Venezuela (Mahaney et al., 2010) is, upon examination, a loosely dated "sandy pebbly bed," with manganese-staining on grain surfaces, within a glacio-fluvial sequence. Holliday and Meltzer (2010) conclude that "[t]he claim for a sudden, synchronous, continent-wide stratigraphic 'event' is very weak."

Our study sections on the California Channel Islands each contain several tens of black-mat-like horizons (see Fig. 2a, b and c) – some of them as well developed and thicker than the single mat at Murray Springs and other sites highlighted by Firestone and colleagues – dating from the LGM to the late Holocene. The overall fluvial architecture of these sequences matches the present-day geomorphology of the associated streams, with localized fill packages and scour surfaces, channel lags, point-bar, and fine-grained overbank/marginal-floodplain horizons. The dark color of these units is not due to charcoal or even preserved organics. TOC measurements from these deposits show most of the dark horizons to be <3 wt.% TOC, with no correlation between organic content and sediment texture or color. Instead the dark color appears related predominantly to clay content and mineralogy, probably mainly pedogenic (aquolls/mollic epipedons). Looking at Murray Springs and other YD-age black mat deposits, Haynes (2008) suggested a climatic signal, driving water levels higher on a regional basis. Alternatively we hypothesize a similar paleo-hydrologic mechanism, driven by YD vegetation shifts and resulting changes in local transpiration, perhaps tied to local Clovis occupation and/or faunal extinctions recorded at those same sites immediately beneath the black mat layer.

3.3.1. Additional results

Our group examined charcoal from the late Pleistocene to early Holocene sections in California previously described (see Fig. 2). As noted above, these sections are close to several of the sites examined by Firestone et al. (2007a), including in Arlington Canyon which was the basis for Kennett et al. (2008, 2009a, 2009b). Charcoal and thus fire are recorded in the Northern Channel Islands field area well back into the Pleistocene, for example charcoal in dune sand dated to 23,377–22,600 cal BP (SMI-4; Table 1). Within the fluvial fill sequences described previously, abundant charcoal is present in or near the basal units that we have dated, for example back to 18,519–17,929 cal BP in Sauces Canyon on Santa Cruz Island, back to 29,222–28,394 cal BP in Verde Canyon and to 17,406–16,823 cal BP in Arlington Canyon on Santa Rosa Island (Table 1). The fluvial architecture of the deposits document predominantly gradual, low-energy aggradation from the LGM through the mid-Holocene. Charcoal is common through the Pleistocene sections, diminishing up into the Holocene deposits, matching a change in fuel source documented by pollen records (Anderson et al., 2010) from mixed conifer forest to brush and grassland.

Reflectance data from the charcoals as well as carbonaceous spherules in the stratigraphic sections above suggest that these materials formed in low-temperature fires with surface temperatures no more than 400 °C (Scott et al., 2010). Scott et al. (2010) measured reflectance of Pleistocene spherules, wood charcoal from the California study sections, and experimentally charred fungal sclerotia. All spherules show reflectance of $<2\%R_o$, consistent with temperatures of <450 °C. Scott et al. (2010) also reported experimental charring of fungal sclerotia that showed that these particles are destroyed at higher temperatures. When sclerotia were charred for 1 h at 350 °C, some rind and cortical cells coalesced, and at higher temperatures (450 °C), the cells thinned and voids appeared. The carbon spherules reported by Firestone et al. (2007a) and Kennett et al. (2008, 2009a, 2009b) lack these characteristics and represent, at most, low-temperature charring. These results preclude claims of high-intensity fire for the origins of carbon spherules (fungal sclerotia) and for charcoalified plant material in YDB-age and other Pleistocene deposits.

3.4. Nanodiamonds

With many of the proposed impact markers encountering strong skepticism, YD impact proponents have increasingly focused upon the reported presence of abundant nanometer-sized (2–300 nm) diamonds (nanodiamonds) at multiple locations across North America as evidence of a YD impact event (Firestone et al., 2007a; Kennett et al., 2009a,b). Formation of diamond by dynamic shock processes (DeCarli and Jamieson, 1961), including nanodiamonds (Greiner et al., 1988), has been demonstrated in the laboratory. Nanodiamonds also have been isolated in acid residues of K–T boundary sediments (Carlisle and Braman, 1991), and micron-sized diamonds have been reported at impact craters (e.g., the Popigai and Lappajärvi impact structure, Koeberl et al., 1997; Langenhorst et al., 1999). Therefore, YD impact proponents interpret the presence of nanodiamonds in YDB sediments as resulting from (1) extraterrestrial processes, or (2) shock synthesis upon terrestrial impact ("may arrive inside the impactor or form through shock metamorphism," Kennett et al., 2009a), or possibly (3) by impact-induced wildfires ("nanodiamonds were produced in the YDB by high temperatures resulting from the impact and associated biomass burning;" Firestone et al., 2007a).

The identification of nanometer-sized grains of diamond in YDB sediments was initially based on ^{13}C nuclear magnetic resonance (NMR; Firestone et al., 2007a), however the observed NMR peaks were broader and occurred at a larger chemical shift than that expected for nanodiamonds (see Cody et al., 2002; Kerr, 2008). Subsequently, impact proponents turned to transmission electron

Table 1
Radiocarbon ages cited in the text.

Lab #	Sample #	Height (m V. datum)	Mat. dated	^{14}C age	±	Calibrated age* (cal BP, 2 sigma)	
Santa Cruz Island Sauces Cyn							
Beta 255165	SCI-07-P17	13.06	Bulk organics	3980	40	4296	4566
Beta 251684	SCI-07-P12	9.85	Bulk organics	8080	50	8772	9234
Beta253071	SCI-07-P8	7.00	Bulk organics	9600	50	10,756	11,160
UCIAMS 65153	SCI-09-07	5.90	Charcoal	11,920	25	13,659	13,896
UCIAMS 46040	SCI-RC-5B	5.00	Charcoal	12,590	60	14,245	15,189
UCIAMS 65152	SCI-09-04	4.00	Charcoal	12,525	30	14,237	15,103
UCIAMS 46051	SCI-07-P4	3.37	Organics from cei	13,080	30	15,221	16,402
UCIAMS 46039	SCI-07-P3	2.25	Organics from cei	13,190	35	15,431	16,616
UCIAMS 46038	SCI-07-Plb (al)	0.92	Organics from cei	13,905	35	16,793	17,163
UC1AMS 48977	SCI-08-1	0.00	Charred wood	14,045	25	16,855	17,422
UCIAMS 48978	SCI-08-2	0.0 (base)	Charred wood	14,910	30	17,929	18,519
Santa Rosa Island Verde Cyn							
Beta 255164	SRI-07-P12	10.55	Bulk organics	1790	40	1605	1823
UCIAMS 46043	SRI-07-P10	7.46	Charcoal	4525	15	5055	5304
Beta 255163	SRI-07-P8	5.3	Bulk organics	7430	40	8179	8345
UCIAMS 65158	SRI-09-01	3.05	Charcoal	8955	25	9926	10,210
Beta 255162	SRI-07-P3	2.6	Bulk organics	9070	50	10,168	10,380
UCIAMS 46041	SRI-07-P1	0.75	Charcoal	20,630	940	22,328	27,031
UCIAMS 65159	SRI-09-12a	0.5	Charcoal	23,950	90	28,394	29,222
Santa Rosa Island Middle Arlington Cyn							
Beta 262767	SRI-09-26	10.0	Bulk organics	10,070	60	11,334	11,962
UCIAMS 66950	SRI-09-28	Corr. section**	Charred wood	11,020	25	12,718	13,079
UCIAMS 66957	SRI-09-94	2.5	Charcoal	14,010	35	16,823	17,406
Santa Miguel Island							
UCIAMS 48980	SMI-4	N.A.	Charcoal	19,280	40	22,600	23,377

* Calibration using Calib v.6.0.0. In conjunction with Reimer et al. (2009).
** Correlative basal section immediately downstream.

microscopy (TEM) to provide evidence of nanodiamonds (Kennett et al., 2009a,b). Using TEM selected-area electron diffraction, Kennett et al. (2009a) reported the cubic diamond polytype (space group 227 — Fd_3m, a = 3.567 Å, designated as 3C) and a previously proposed modification of the diamond structure, termed "n-diamond" (or fcc carbon; see Yamada and Sawaoka, 1994; Konyashin et al., 2006), as abundant in YDB sediments. Kennett et al. (2009b) later reported the rare hexagonal diamond polytype, lonsdaleite (space group 194 — $P6_3/mmc$, a = 2.52 Å, c = 4.12 Å, designated as 2H) present in YDB sediments. Lonsdaleite is particularly interesting because it is often associated with impact shock features where it has been found to occur naturally (see Bundy and Kasper, 1967; Frondel and Marvin, 1967; Hanneman et al., 1967; Erlich and Hausel, 2002). There are a few reports in the Russian literature of lonsdaleite occurring within yakutite carbonados; titanium placers of the Ukrainian shield; diamond placers in Yakutiya; and ecolgites in Sal'niye Tundra, Kola Peninsula, and the Urals (for a review, see Kaminsky, 1991; Erlich and Hausel, 2002).

The YBD nanodiamonds have been reported within carbonaceous grains (carbon spherules, "glass-like carbon", and in their so-called "carbon elongates") at Lake Hind, MB, Canada, Murray Springs, AZ, Bull Creek, OK (Kennett et al., 2009a), and Arlington Canyon, CA (Kennett et al., 2009b). Nanodiamonds have also been reported in YDB bulk sediment at Murray Springs, AZ, Bull Creek, OK (Kennett et al., 2009a), and at various Carolina Bays (Firestone, 2009). Kennett et al. (2009a,b) reported that their nanodiamond concentrations peaked at ~10 to 3700 ppb at the YDB (absent above and below the boundary) and at ~100 to 200 ppb in YDB bulk sediments. However, no details were provided on the methodology for measuring ppb concentrations of nanodiamonds (measurement at ppb concentrations is not trivial) and, as such, it is not possible to evaluate accuracy/reliability of those measurements.

The reports of nanodiamonds in YDB sediments (Firestone et al., 2007a; Kennett et al., 2009a,b) lacked a number of key details (e.g., see above) and left many unanswered questions regarding the nature and occurrence of the nanodiamonds. For this reason, Daulton et al. (2010) performed a detailed TEM microcharacterization of carbonaceous materials (carbon spherules, microcharcoal, and glassy carbon) from YDB black mats and other dated sources (see Table 1) to independently address the question of nanodiamonds in YDB sediments and in sediments of other ages. In that work, microcharcoal aggregates were isolated from the base of black mat sediment layer at the same locality (Murray Springs) reported to contain cubic nanodiamonds (Kennett et al., 2009a), and carbon spherules were isolated from the same area (Arlington Canyon, Santa Rosa Island, CA) reported to contain hexagonal nanodiamonds (Kennett et al., 2009b). Daulton et al. (2010) showed that the carbonaceous phases in carbon spherules and microcharcoal isolated from YDB-age deposits are identical to those in spherules and glassy carbon isolated from older sediments as well from a modern forest fire (Thursley Bog; Scott et al., 2010). All specimens were predominantly C and contained the same dominant minerals: amorphous carbon (a-C), graphene, graphene/graphane, and graphite with all but the former displaying varying degrees of disorder.

The dominant crystalline carbonaceous-phase observed in YDB carbons was graphene in the form of polycrystalline aggregates (Figs. 1 and 2 in Daulton et al., 2010; Table 2). Graphene is a two-dimensional, single-atom-thick planar molecule with sp^2 bonded carbon (1.42 ± 0.1 Å bond length) in a hexagonal arrangement of 2.46 ± 0.02 Å edge length (Geim and Novoselov, 2007; Elias et al. 2009). In the form of a polycrystalline aggregate, as first observed in the cores of many circumstellar graphite spherules isolated from chondritic meteorites (Bernatowicz et al. 1996), graphene sheets are randomly oriented and lack any correlation. When periodically stacked normal to their plane (e.g., *AB*, *AA*, or *ABC* stacking), graphene sheets form various graphite polytype structures or turbostratic graphite if the stacking is disordered. A modified form of graphene (present within some graphene aggregates) was also observed that exhibited a 5.1 ± 0.3% (see Table 2) contraction in hexagonal edge length, although the contraction varied somewhat from aggregate to aggregate. This is consistent with the previously theorized but only recently synthesized hydrogenated form of graphene, termed graphane (Elias et al., 2009). The third most abundant crystalline carbonaceous phase was graphite with various degrees of graphene-sheet stacking disorder.

Neither 3C cubic nor 2H hexagonal diamond was identified in any of the samples. In one specimen, a nanocrystalline aggregate was observed with diffraction spacings similar to those of the proposed n-diamond, however that aggregate was identified as nanocrystalline Cu. It is possible nanodiamonds occur inhomogeneously and only in some of the YDB carbons, and hence were not observed by Daulton et al. (2010). However, Kennett et al. (2009b) describe the occurrence of nanodiamonds in carbon spherules: "…a TEM study revealed conspicuous subrounded, spherical, and octahedral crystalline particles (2–300 nm) distributed in their carbonaceous matrices…" and "Analysis of the particles by electron diffraction shows reflections consistent with cubic diamonds…". They also state, "lonsdaleite crystals at Arlington co-occur with carbon spherules and other diamond polymorphs…."

While it is intrinsically difficult to prove the complete absence of a mineral in a sediment (at best, upper limits to its size and concentration can be constrained), Daulton et al. 2010 demonstrated that previous TEM studies of YDB sediments (Kennett et al., 2009a,b) misidentified graphene/graphane aggregates, ubiquitous in several types of carbon-rich materials from sediments as 2H hexagonal diamond (Figs. 3 and 4 in Daulton et al., 2010). Previous studies also may have misidentified graphene as 3C cubic diamond. The observations that YDB-age carbons

Table 2
Nanodiamond test samples — ^{14}C and calibrated ages.

Laboratory/specimen number	Height (m above datum)	Material dated	^{14}C Age (years)	Calibrated age (cal yr BP: 2-sigma)[a]
Santa Cruz Island Sauces Canyon[b]				
UCIAMS 46051/SCI-07-P4	3.37	Organics from centrifuge	13,080 ± 30	15,221-16,402
Santa Rosa Island Middle Arlington Canyon[b]				
UCIAMS 66950/SRI-09-28	Near basal	Charred wood	11,020 ± 25	12,718-13,079
UCIAMS 66951/SRI-09-29c	Near basal	Charcoal[c]	11,625 ± 25	13,341-13,619
Murray Springs				
Basal black mat deposit	Near basal		10,260 ± 430[d]	
			11,000 ± 100[d]	
			10,410 ± 190[d]	

[a] Using *Calib* v6.0 calibration software (Reimer et al. 2009).
[b] Daulton et al., 2010.
[c] Scott et al., 2010.
[d] Haynes, 2007.

Table 3
Electron diffraction planar spacings.

Diamond		Graphene/graphane — oxide					
Indices	Calculated (Å)	Indices	Calculated graphene (Å)	Presolar graphene (Å)[a]	Younger Dryas graphene (Å)[a,b]	Younger Dryas graphane (Å)[a,b,c]	Calculated graphane (Å)
111	2.053	100	2.130	2.033 (6)	2.076 (4)	2.004 (7)	2.021
220	1.257	110	1.230	1.230 (2)	1.222 (2)	1.158 (2)	1.167
311	1.072	200	1.065	1.069 (3)	1.061 (2)	0.991 (3)	1.011
400	0.889						
331	0.816	120	0.805	0.807 (2)	0.798 (1)	0.754 (2)	0.764
422	0.726	300	0.710	0.709 (2)	0.705 (1)	0.657 (1)	0.674
511/333	0.684						
440	0.629	220	0.615	0.616 (1)	0.609 (1)	0.575 (2)	0.587
531	0.601	130	0.591	0.593 (1)	0.584 (1)	0.547 (5)	0.561
620	0.562						
533	0.542	400	0.533	0.534 (1)	0.525 (1)	0.496 (2)	0.506
444	0.513						
551/711	0.498	230	0.489	0.489 (1)	0.479 (1)	0.460 (1)	0.464
642	0.475						
553/731	0.463	140	0.465	0.465 (1)	0.455 (1)	0.436 (6)	0.441
800	0.445						
733	0.434	500	0.426	0.427 (1)	0.418 (1)	0.400 (1)	0.404
660/822	0.419	330	0.410	0.410 (1)	0.397 (1)	0.381 (1)	0.389

[a] Detonation synthesized nanodiamonds were used to calibrate diffraction camera length of microscope. Values in parenthesis are the measurement error (in the least significant digit) based on standard error of replicate measurements and the error in camera length calibration (±0.2%).
[b] Hexagonal edge length varies slightly from grain to grain.
[c] Measured from graphene/graphane aggregates.

are mineralogically similar to older as well as modern spherules and lack independent evidence for the presence of diamonds (particularly the 2H polytype) cast significant doubt on the YD impact hypothesis (Table 3).

Recently, new claims of nanodiamonds in YD materials were presented in Kurbatov et al. (2010) and Tian et al. (2010). Kurbatov et al. (2010) report nanocrystals isolated from surface sampling the Greenland glacial margin (preliminary results were shown in NOVA's "The Last Extinction"). These nanocrystals were described as "a discrete layer of free nanodiamonds," including lonsdaleite and n-diamonds "at abundances of up to about 5×10^6 times background levels" in ice that they date to the onset of the YD. One initial concern with these results is that, despite claims regarding chronology, in fact no age control was present. Identification of the YD was based on dust in a ~1 m thick ice layer. Such attenuated ice-marginal sections must be regarded as highly suspect – the YD is recorded by up to 100 m of ice in Greenland ice cores – and in fact the purported YD oxygen-isotope values in Kurbatov (−33 to −32‰) are more typical of the Holocene. In addition, nanodiamond samples in Kurbatov et al. (2010) were apparently processed, analyzed, and identified by the same investigators as in Firestone et al. (2007a) and Kennett et al. (2009a,b). Contrary to claims of Kurbatov et al. (2010), the EELS C–K edge spectra of the Greenland ice nanocrystals differs from that reported for the proposed n-diamond. In particular, Kurbatov et al. (2010) observed a relatively strong $1s$–$2p(\pi^*)$ transition characteristic of sp^2 bonded carbon that is absent in the spectra reported by Peng et al. (2001). The C–K edge spectrum also lacked features in the edge fine structure produced by $1s$–$2p(\sigma^*)$ transitions of sp^3 bonded carbon characteristic of diamond (see Egerton, 1996). Instead, their EELS C–K edge is consistent with amorphous carbon with sp^2 bonded components (see Egerton, 1996), as is typical of many TEM carbon support films such as that used to support the nanocrystals. Setting these inconsistencies aside, a more quantitative discussion on the nature of the observed nanocrystals would require access to the original samples for a detailed, independent microanalysis.

Finally, Tian et al. (2010) examined deposits at Lommel, Belgium and identified cubic diamonds from 5 to 100 nm in diameter in YDB-age sediments. They found neither lonsdealite nor n-diamonds and echoed Daulton et al. (2010) that purported hexagonal diamonds in Kennett et al. (2008, 2009a,b) appear to have been misidentified. Stable carbon isotopes, C/N values, and Ir concentrations in the Lommel YDB stratum "fall completely within the range of terrestrial organic matter" (Tian et al., 2010). Cubic nanodiamonds were also identified in surface soils (i.e., modern or recent deposits) at Lommel and other sites in Belgium and Germany (Yang et al., 2008; Tian et al., 2010). At present, a number of questions remain regarding the nature and distribution of cubic nanodiamonds in terrestrial sediments and the processes that formed them.

4. Discussion

The assessment here of the YD impact hypothesis was framed as three possible outcomes for each type of evidence originally proposed. Subsequent rigorous testing could have: (1) corroborated the original claim, (2) confirmed the physical evidence but suggested alternative mechanisms (e.g., no impact necessary), or (3) the original evidence could have proved non-reproducible (Table 4). Of the 12 lines of evidence originally proposed, none has been confirmed by other independent, mainstream researchers (Outcome 1 above). In contrast, at least 7 of the 12 lines of evidence could not be reproduced or have been directly contradicted by subsequent independent tests (Outcome 3). Particle entrance "wounds", magnetic "bullets," ^{3}He and fullerenes in YD material, YDB radioactivity and Ir peaks, and most recently hexagonal and n-type nanodiamonds should be regarded as unsubstantiated or simply erroneous. The remaining pieces of YD evidence seem to fall into Outcome 2 — they have been seen by other workers but attributed to alternative (non-impact) causal mechanisms. The Carolina Bays, for example, certainly exist, but extensive previous research – and the impact proponents' own new ^{14}C dates – argue strongly against an impact origin. The existence of carbon spherules and "carbon elongates" has been confirmed, but they are ubiquitous in Pleistocene to modern sediments, are of biological origin, and did not originate in catastrophic wildfires. Similarly, metallic microspherules do exist, but they are not unique to the YD, do not represent impact evidence, and the purported frequency peaks in YDB deposits cannot be reproduced.

The discrepancies between the original YD impact data and interpretations and the subsequent assessments of the same materials raise questions about how such differences could arise. In the starkest cases here, for example side-by-side re-measurements by Surovell et al. (2009) and Haynes et al. (2010), the discrepancies with the original

Table 4
Outcomes of original 12 lines of evidence presented in support of the Younger Dryas impact hypothesis.

	Outcome 1 (claims corroborated)	Outcome 2 (observations reproduced, but consistent w/non-impact mechanism[s])	Outcome 3 (original evidence non-reproducible)
(i) Particle tracks in archeological chert			X
(ii) Magnetic nodules in tusk and bone		X	
(iii) Fullerenes			X
(iv) 3^He			X
(v) Iridium peaks		X	X
(vi) Radioactivity peaks			X
(vii) Carolina Bays		X	
(viii) Carbon spherules/elongates, glassy C		X	
(ix) Magnetic grains		X	
(x) Magnetic microspherules		X	
(xi) “Mega-fire” byproducts		X	
(xii) Nanodiamonds			X

studies defy explanation at the present time. As outlined above, however, most of the original observations were basically replicable but, most researchers would now argue, were misconstrued to suggest a catastrophic impact, when in fact no such event was required or even allowed by the data. In retrospect, a few common themes seem to emerge: (1) materials resulting from gradual processes were instead interpreted as evidence of catastrophic event(s); (2) terrestrial materials were instead interpreted as extraterrestrial in origin; and (3) accepted impact signatures – documented across the Earth and other planetary surfaces and back through geological time – were never found, requiring YD impact proponents to suggest novel, contradictory, and fast-changing impact scenarios. We explore these themes below.

4.1. Catastrophic vs. non-catastrophic mechanisms

Perhaps the clearest example of YD impact research eschewing gradual, uniformitarian explanations is its claim for catastrophic wildfires, triggered by the purported impact, ranging from California to Europe. Where fire is recorded in the latest Pleistocene, such as in the California sections presented here, it pre-dates and post-dates the YDB, with no evidence presented of anomalous, high-intensity fire at the boundary itself. Evidence that was originally presented as new indicators of catastrophic fire was misidentified, with “carbon spherules” and “carbon elongates” in reality representing fungal sclerotia and/or arthropod coprolites. In fact the morphologies and reflectance of YDB-age carbon spherules, as well as charcoal, document at most low-intensity burning. Similarly, the distinct dark-colored “black mat” deposits at a number of Clovis-age sites across the western U.S. (Haynes, 2008) do not represent a paleo-fire event. Although a singular horizon at some locations, multiple equivalent dark layers are present at many other sites, dating from the late Pleistocene through the Holocene. And rather than recording “extreme wildfires [which] decimated forests and grasslands, destroying the food supplies of herbivores and producing charcoal, soot, toxic fumes, and ash” (Firestone et al., 2007a), these dark and fine-grained deposits typically represent paleo-wetland deposits with various degrees of mollisolic input and pedogenesis. More broadly, fire signatures used to support the YD impact story have been pulled selectively from diffuse fire markers scattered through many late Pleistocene sequences, fire being an episodic but widespread process across many landscapes and back through time (Bowman et al., 2009; Scott, 2010).

Another example where YD impact proponents jumped to a catastrophic causal mechanism was for their “magnetic/metallic microspherules.” At the May, 2007 AGU meeting at which the YD hypothesis was announced, Firestone (2007) stated that “We have more microspherules … than the rest of the world has collected in all of their [sic] research.” In actuality, glassy and metallic spherules are abundantly documented throughout the geological record: in Antarctic ice (e.g., Taylor et al., 1998), in deep-sea sediments (e.g., Petterson and Fredriksson, 1958), in peat-bog sequences (e.g., Franzén, 2006), and other depositional environments with low clastic input (see French and Koeberl, 2010). This material results from the regular input of micrometeorites through the atmosphere, which ablate in the atmosphere and settle to the earth's surface at rates estimated at roughly 30,000 tons/year (Love and Brownlee, 1993). Spherules also derive from numerous anthropogenic processes and products, and are well known and abundant in modern coal fly ash and emissions from coal-burning power plants (Crelling, 2010).

Pinter and Ishman (2008a,b) first pointed out that all of the YD spherules reported as evidence of a catastrophic YD impact event were consistent with the diffuse, constant, and non-catastrophic input of micrometeorite ablation fallout. This input of ablation spherules was probably augmented by anthropogenic spherules in YDIH samples with significant modern content (e.g., the Carolina Bays; see discussion above).

The critical point above is that the presence of spherules alone cannot be used as an ET impact marker (Pinter and Ishman, 2008a; French and Koeberl, 2010). Instead, the true test of the YD impact hypothesis is the assertion by its proponents that spherules and magnetic grains peak in the YDB, with zero or very significantly lower counts in the under- and overlying units. For example, Kennett et al. (2008) and Firestone (2009) claim that Haynes (2008) “identified peaks in metallic microspherules at the [YDB];” in fact, Haynes (2008) identified the presence of spherules at the YDB in the Murray Springs sequence and made no statements about their distribution. To date, magnetic spherule concentrations that peak uniquely at the YDB have only been identified by the Firestone and Kennett group. The same is true for magnetic grains, iridium concentrations, radiation levels, wildfire indicators, and carbon spherules and elongates (a.k.a. fungal spherules and arthropod coprolites; Scott et al. (2010)). Subsequent reanalyses have shown that all of these signatures are present before and after 12,900 years ago.

4.2. Terrestrial vs. ET mechanisms

Another common theme in the YD impact hypothesis, and in the range of markers used to identify it, is the attribution of terrestrial material to purported ET sources. In the case of the magnetic spherules, our results suggest that separation using a neodymium magnet and identification of candidate spherules using reflected-light microscopy may capture significant numbers of terrestrial particles. Although the reflected-light approach used by Firestone et al. (and by Surovell and by us, duplicating the Firestone methodology) identifies grains that are highly spherical at the limits of optical-microscope magnification, SEM reveals that some candidate microspherules have complex fine-scale structure (see Fig. 5). EDS and XRD of the spherular grain illustrated in Fig. 5 suggested a pyritic composition,

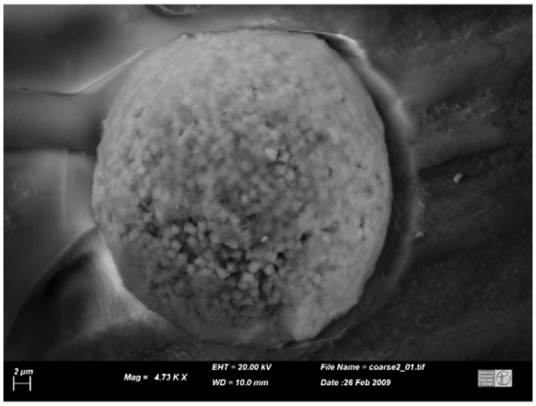

Fig. 5. SEM image of weakly magnetic spherule from the latest Pleistocene section in Sauces Canyon, Santa Cruz Island, CA. Although this particle met the criteria for identification outlined in Firestone et al. (2007a), including smooth and sharply reflected surface under an optical microscope, the surface texture is framboidal at higher resolution. Micro-XRD of this sample showed it to be composed primarily of pyrite, consistent with the framboid texture, and suggestive of a biological (algal) origin.

and the texture of the grain is framboidal, inconsistent with ablation fallout but rather with algal activity. In contrast to spherules reported from sediment-free, pre-historical glacial ice, terrestrial sedimentary sequences may include an unknown number of additional spherical forms derived from *in situ* processes, known and unknown.

After Surovell et al. (2009) failed to find any peak in the abundance of magnetic spherules in any YDB deposits, Firestone responded that Surovell and colleagues "used the wrong protocol to look for microspherules … looking for shiny, perfectly spherical examples. The ones we found were often pitted, not perfect spherules, and not shiny" (R. Firestone, open email dated 10/13/09; emphasis added). Surovell et al. (2009) commented on the high degree of subjectivity in identifying spherules using the technique outlined in Firestone et al. (2007a), and both their analyses and ours opted for the strictest standard possible — highly spherical and smooth grains that provided a distinctive signature under reflected-light microscopy. We rejected numerous rounded to sub-rounded magnetic grains with rough or pitted surfaces. In a separate test, we collected material from a heavy-mineral lag on sand dunes from the western Basin and Range (see Fig. 6b). A large portion of this material was magnetic, and many of these sand-sized grains were – like the accompanying silicate grains – very well rounded (Fig. 6a). Compositional analysis of several well rounded sand-dune grains documented clear detrital mineral signatures such as magnetite. Without a strict distinction between clear and unweathered cosmic spherules and the much larger potential population of rounded detrital magnetic grains, spherule counts such as those presented by Firestone and colleagues may include a large number of terrestrial grains in addition to true ET fallout spherules.

4.3. Impact signatures at the YDB

As impact cratering studies have entered the mainstream of geological research, diagnostic criteria were developed for the identification and confirmation of impact structures and ejecta on Earth (see reviews in, e.g., Stöffler and Langenhorst, 1994; Koeberl, 2007; French and Koeberl, 2010). These criteria are clearly defined: only the presence of diagnostic shock-metamorphic effects and, in some cases, the discovery of meteorites, or traces thereof, are generally accepted as unambiguous evidence for an impact origin. Shock deformation can be expressed in macroscopic form (shatter cones) or in microscopic forms (e.g., distinctive planar deformation features [PDFs] in quartz). None of these have been found in the YD deposits.

The presence of meteoritic debris and other extraterrestrial signatures at the YDB were proposed but have encountered several problems, as detailed above. The presence of micrometeorites or meteorite fragments have neither been confirmed, nor do they represent unambiguous impact evidence. The presence of a chemical extraterrestrial signature in the form of Ir (and PGE) anomalies was not confirmed. The presence of a possible (but still unconfirmed) Ir anomaly in magnetic separates is irrelevant as this could either represent the presence of meteoritic ablation spherules which represent normal background flux, or terrestrial mineral assemblages. As noted by French and Koeberl (2010), the presence of exotic compositions, e.g., rare-metal alloys, hydrocarbons or enrichments in non-meteoritic elements such as Ba, Ti, Mn, and Pb suggests a natural or artificial terrestrial origin. The YD impact proponents have suggested a host of unusual explanations for the (e.g., Ti-rich) composition of the YD spherules measured by them, including the suggestions that nuclear reactions from supernova explosions created these compositions, or that the impactor possessed an unusual chemical composition similar to lunar KREEP rocks. Such a suggestion contradicts other lines of "YD impact evidence", and seems to present an insurmountable physical problem of how to transfer KREEP rocks, which are very rare on the Moon and constitute a minute component of known lunar meteorites. Lunar rocks do not contain high Ir or other PGE abundances. Further, it is hard to believe that a lunar rock 4–5 km in diameter could be ejected from the Moon, then explode in the

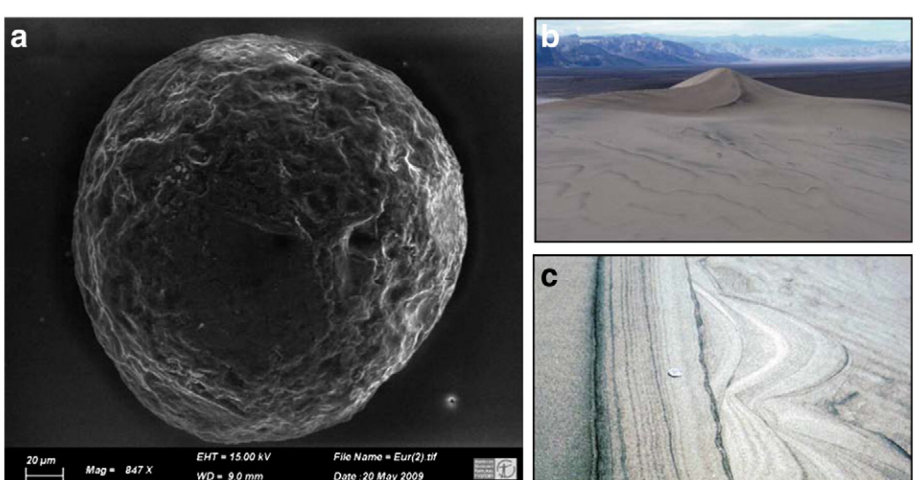

Fig. 6. "Pseudo-spherule" from modern sand from Eureka Dunes, California. Significant quantities of heavy minerals are concentrated as eolian lags and include abundant very well rounded mineral grains. EDS analysis of this grain shows it to be magnetite and of detrital origin.

Earth's atmosphere without leaving any traces but a few Ti-rich spherules.

The nature of the proposed YD impact/airburst event and the proposed impactor also require careful scrutiny. Most recently, YD impact proponents have suggested that the impact body was a 4.6 km diameter comet core (Firestone, 2009) or, alternatively "multiple 2-km [diameter] objects" (Firestone et al., 2010). An impact body this size would not be significantly impeded by the Earth's atmosphere because the body diameter is almost the scale height of the atmosphere (e.g., Melosh, 1989). A body of this size collides with the Earth at very high velocity; comets in particular because they are on highly elliptical orbits, resulting in velocities of about 40 km/s. Cratering mechanics (e.g., Melosh, 1989) indicate that a 4.6 km diameter impactor will, on average, result in a crater of 50–100 km in diameter. Even if a 2-km-thick ice sheet would have been part of the target, the transient cavity of such a crater would still have been at least 10 km deep. A crater of this size, being that young, would be hard to overlook on the Earth's surface — a few possible holes "deeper than Death Valley" on the floor of the Great Lakes (Firestone, 2009; Firestone et al., 2010) do not qualify. And impact melt rocks in such a large young crater would still preserve a thermal anomaly.

Craters in the 50–100 km diameter range are not common on Earth. Impact flux estimates based on the past cratering rates indicate that impacts of this magnitude happen only at intervals of ~10 Ma, and only half a dozen craters of this size are known on Earth from the past 50 Ma (Earth Impact Database, 2010). The alternative suggestion, also made by the YD impact proponents, is that there were many small bodies. Such an explanation raises other questions. Among them, where would the shock come from to form the purported diamonds, as an explosion in the atmosphere does not provide sufficient shock pressures. On the other hand, a crater-forming event on the ground would shock much more than some graphite to form diamonds. If so, where are the common and usually abundant shock indicators, such as shocked rocks and minerals? The YD impact hypothesis has gained little traction in the mainstream impact science community because it eschews tested and accepted impact evidence. In the face of growing contradictory evidence, YD impact proponents have presented a range of rapidly changing *ad hoc* explanations which contradict documented impact processes, contradict each other, and in many cases contradict the laws of physics.

5. Conclusions

In the time since the YD impact hypothesis was proposed, a number of independent researchers have tested and attempted to corroborate the evidence presented in support of such an impact. In this paper, we reviewed the original evidence as well as the results to date of those subsequent tests. Three years ago, many workers regarded at least some of the original YD impact claims with cautious skepticism, but there was universal agreement that subsequent analyses were needed and that the outcome of the impact story remained open at that time. At present, a clearer picture has emerged on the validity of these claims. One by one, the information originally presented as evidence of a catastrophic YDB impact event have failed attempts at corroboration.

The original 12 lines of YD evidence were highly diverse, based on work by many different workers, and some of these results quickly came into doubt, apparently even internally by other YD proponents. Megafaunal bones with magnetic nodules, for example, were dated much older than 13,000 cal BP, and ^{3}He-enriched fullerenes had been largely discredited by specialists in the field even before entering the YD impact debate. Four types of purported evidence, however, remained in vigorous discussion: (1) carbon spherules and other carbonaceous forms reported in YDB deposits, (2) nanodiamonds in those carbon forms, (3) concentrations of magnetic microspherules, and (4) purported evidence of continental wildfire. As reported in Scott et al. (2010) and elaborated here, carbonaceous spherules and so-called carbon elongates may indeed be present in YDB deposits, but they are indistinguishable from common forms – fungal sclerotia and arthropod fecal material – which are ubiquitous in deposits of a wide range of ages, including modern materials. Similarly, most or all of the material reported by Firestone et al. (2007a) and Kennett et al. (2008, 2009a,b) as nanodiamond likely consists instead of graphane and/or graphene, representing a misinterpretation of both the original NMR and later TEM data (Daulton et al., 2010). Peaks in the concentrations of magnetic microspherules reported at the YD boundary could not be reproduced by Surovell et al. (2009) nor by Haynes et al. (2010), and we report equal or greater concentrations of microspherules in similar fine-grained terrestrial deposits spanning several thousand years through the terminal Pleistocene and into the Holocene. Finally, it is shown here that the catastrophic impact-ignited wildfires reported at the YDB represent (1) a misinterpretation of local "black mat" deposits, combined with (2) widespread and diffuse evidence of low-intensity fires present in most or all of the sequences studied. The black mat deposits are not organic-rich, paleo-burn horizons at all, but rather are wetland paleosols that contain only local and diffuse fire material such as charcoal. In our California field area, fire activity is documented by charcoal that is widespread well before 13,000 cal BP as well as after. Similar patterns have been documented in regional fire records across North America as well as Europe.

The evidence supporting the YD impact hypothesis seem to reflect two common themes. First, several types of material that can result from gradual and non-catastrophic processes were instead interpreted as unique signatures of a catastrophic (impact) event. Second, a number of materials of terrestrial or ambiguous origin were instead interpreted as directly or indirectly extraterrestrial in origin. In both cases, demonstrably widespread materials were reported as strongly concentrated at the time horizon of interest (the YDB). Originally, many YD skeptics had thought that some alternative event – perhaps even a smaller impact – might have occurred at 12,900 cal BP. The collapse of all supporting evidence to date, however, suggests that no event in any way resembling the purported impact appears to be recorded at the onset of the YD.

Research through the past century has documented the significance of extraterrestrial impact events in shaping the Earth's surface, climate, and life through geological time. A widespread problem, however, is that some researchers, when confronted with any unusual geological evidence, too readily jump aboard the "impact bandwagon" (Koeberl, 2004; Reimold, 2007). As one impact scientist has put it, "Too many people seeing too many circles." The spectacular nature of impact events typically mean that these claims receive disproportionate and often premature attention in the popular press and media (Pinter and Ishman, 2008a). We reiterate here that impact research, just like other areas of the geosciences, must adhere to a rigorous approach based on clear and unambiguous criteria, which has not been the case for the YD impact hypothesis.

This paper has systematically reviewed evidence presented as signatures of a YD impact event, and this review has been framed as a "requiem," suggesting the end of the YD impact hypothesis. It is fair then to ask whether we are indeed seeing the end of this hypothesis. As for some proponents, the answer is certainly 'no' — several have stated that they will continue their quest until the hypothesis is confirmed. Some insight is gained by adding a historical perspective here. Scientific hypotheses are constantly being proposed, tested, confirmed, or cleanly rejected, but a small minority of these stray from this time-proven path. Many scientists are unaware of the surprising number of hypotheses that have gone badly astray, often after widespread initial interest and support (Langmuir and Hall, 1989; Gratzer, 2000; Park, 2000). Characteristics of these wayward hypotheses include claims that are spectacular, data that are subjective or at the limit of precise measurement, and criticisms met with *ad hoc* excuses and/or shifts in the original claims (after Langmuir and Hall, 1989). We suggest that much can be gained by stepping back and looking at the broader lessons for the earth sciences, impact science, archeology, and other affected fields.

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