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Fungus, not comet or catastrophe, accounts for carbonaceous spherules in the Younger Dryas "impact layer"

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[1] A claim attributes the onset of the Younger Dryas climate interval and a range of other effects ~12,900 years ago to a comet airburst and/or impact event. One key aspect of this claim centers on the origin of carbonaceous spherules that purportedly formed during intense, impact-ignited wildfires. Samples from Pleistocene-Holocene sedimentary sequences in the California Channel Islands and other sites show that carbon spherules and elongate forms are common in samples dating to before, during, and well after the 12,900-year time horizon, including from modern samples. Microscopic studies show that carbon spherules have morphologies and internal structures identical to fungal sclerotia (such as *Sclerotium* and *Cenococcum*). Experimental charring of fungal sclerotia shows that their reflectance increases with temperature. Reflectance measurements of modern and late Pleistocene spherules show that the latter indicate, at most, low-intensity burning. These data cast further doubt upon the evidence suggesting a catastrophic Younger Dryas impact event.
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1. Introduction

[2] Central to the proposed impact event 12,900 calendar years before present (cal BP) [*Firestone et al.*, 2007; *Kennett et al.*, 2008, 2009a, 2009b] has been the suggestion of catastrophic wildfires "ignited by an intense radiation flux associated with a cosmic impact"[*Firestone et al.*, 2007], fires that ranged from coastal California, across North America, to Europe. Putative evidence of these hemisphere-spanning fires includes "charcoal, soot, carbon spherules, and glass-like carbon, all of which suggest intense wildfires". The carbon spherules in the Younger Dryas (YD) deposits (Figures 2a–2c) are described as "black, highly vesicular, subspherical-to-spherical objects … [with] cracked and patterned surfaces, a thin rind, and honeycombed (spongy) interiors … with no evidence of seed-like morphology or cellular plant structure" [*Firestone et al.*, 2007]. In addition, *Kennett et al.* [2008, 2009a, 2009b] identified "carbon elongates" (a new term) which, like the spherular forms, "have (1) the appearance of melted and charred organic matter, (2) a moderately glossy shell unlike that of charcoal, and (3) interior vesicles that are typically a few micrometers in diameter" [*Kennett et al.*, 2008].

[3] We studied three sedimentary sections from the Northern Channel Islands (NCI; Figure 1) of California: at Sauces Canyon on Santa Cruz Island and at Verde Canyon and Arlington Canyon on Santa Rosa Island, as well as samples from modern collections. The NCI contain two of the type sections studied in detail by the Firestone group – Arlington Canyon on Santa Rosa Island and Daisy Cave on San Miguel Island – both of which reportedly contain charcoal, black carbon spherules, nanodiamonds, and other purported fire and impact markers at the 12,900 Cal BP horizons [*Firestone et al.*, 2007; *Kennett et al.*, 2008, 2009a, 2009b]. The sections in Arlington Canyon, Verde Canyon, Sauces Canyon, and a number of additional nearby sections that we also examined, are fluvial fill sequences deposited from the late Pleistocene to the Holocene. We measured and described these sections, collecting material for separation of charcoal and other organic forms as well as for radiocarbon dating. In addition, samples of modern fungal sclerotia were assembled and experimentally charred at 350–800°C for a range of times. Carbon spherules and other forms from all samples were structurally characterised using reflected light microscopy, Scanning Electron (SEM), and Transmission Electron (TEM) and some using Synchrotron Radiation X-ray Tomographic Microscopy (SRXTM) and then compared with the samples previously described at the YD impact horizon and with reference materials from the literature and from comparative collections from sites worldwide (auxiliary material).[9]

2. Results

[4] Litter and soils contain many spherical and elongate particles of biological origin that are not seeds or wood. For

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[9]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043345.

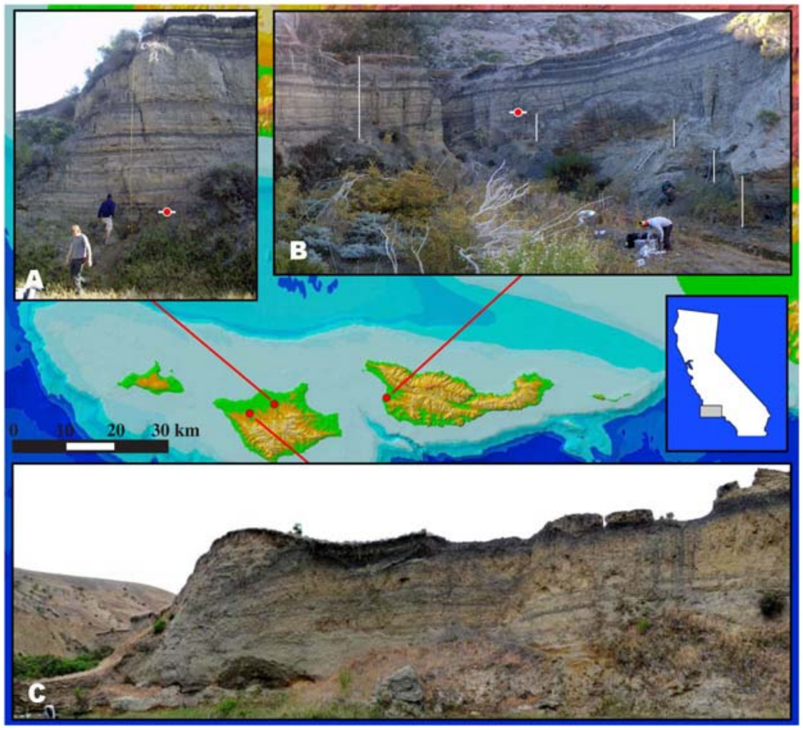

Figure 1. The Northern Channel Islands (NCI) of California, showing portions of the three main sections sampled, dated, and described in this paper. (a) Verde Canyon section on Santa Rosa Island. (b) Sauces (a.k.a. Willows) Canyon on Santa Cruz Island. (c) Middle Arlington Canyon on Santa Rosa Island. Also shown on each plot (red circle) is the approximate position of the 12,900 cal BP age horizon.

example, fungal sclerotia occur commonly at the soil-litter interface [*Watanabe et al.*, 2007]. In the USA, the fungal genus *Sclerotium*, for example, has been reported associated with over 270 host genera [*Farr et al.*, 1989]. Fungal sclerotia may vary in shape but are commonly spherical and in the size range 200 μm to 2 mm [*Townsend and Willetts*, 1954; *Willetts*, 1969; *Watanabe et al.*, 2007]. Also arthropod faecal pellets are often abundant in soils, usually elongate but occur in the same size range depending on the animal responsible: mites, collembola, termites, millipedes [*Adams*, 1984; *Collinson*, 1990; *Scott*, 1992].

[5] Sclerotia of *Sclerotium* and other fungal genera (e.g., *Rhizoctonia*, *Botrytis* and *Cenococcum)* have thick rinds and, depending on stage of development [*Willetts*, 1969; *Massicotte et al.*, 1992], show different internal structure (Figures 2g–2j and 2l–2n and auxiliary material). A thick outer skin or rind of thick-walled cells in *Sclerotium rolfsii* [*Willetts*, 1969] (auxiliary material) overlies thinner walled cortical cells consisting of closely packed hyphae [*Willetts*, 1969]. TEM shows that the outer rind also consists of closely packed hyphae (auxiliary material). In some cases the thinner-walled cortical cells form an irregular meshwork internally. When spheres are subjected to 1 hour charring at 350°C some of the rind and cortical cells coalesce (Figures 2i and 2j and auxiliary material). The uncharred surface appears as a continuous cuticle, which may possess ridges and troughs [*Willetts*, 1969]. However, on charring, even at low temperatures for short periods (350°C for 5 mins), the surface becomes more smooth and glassy in appearance, and the colour changes from deep brown to black (Figure 2h). The thinner-walled cortical cells may appear regularly arranged externally but form an irregular meshwork internally. With longer charring at low temperatures, some of the cells appear to coalesce (Figures 2i and 2j), however at higher temperatures (450°C) the cells thin and voids appear in the spherules (auxiliary material). Sclerotia surfaces of *Botrytis* [*Willetts*, 1969; *Chet*, 1975] and *Sclerotium* show similarities to surfaces illustrated by *Kennett et al.* [2009a]. *Chet* [1975] described sclerotia with relatively large thin-walled cortical cells where the outer surface sometimes shows the presence of small balls. These represent closely packed hyphal tips, which sometimes have a film over them [*Willetts*, 1969]. This surface pattern is similar to some spheres from Santa Cruz Island (auxiliary material) but is lacking on most fossil spheres. The pattern can be seen on uncharred fungal sclerotia (auxiliary material) but is lost in the charred specimens (even those charred at 350°C for 5 min) explaining its absence in many fossils.

3. Implications of Data

[6] Systematic sampling, dating, observation, microscopy and reflectance measurements on black carbon spherules from the NCI study area and from the Thursley Bog fire in Britain, and comparison with the reported YD spherules suggest six key problems with the *Firestone et al.* [2007] and *Kennett et al.* [2009a, 2009b] interpretations.

[7] First, our results confirm that carbon spherules – as well as carbon “elongates”– are not unique to 12,900 cal BP “impact” event horizon in California or elsewhere. We have found spherules (200 μm–2 mm diameter) from multiple horizons in all three of our NCI stratigraphic sections (auxiliary material). The spherules are not unique to a single layer but occur associated with charcoal resulting from

periodic wildfire events (auxiliary material). Fire is an important Earth System Process [*Bowman et al.*, 2009] and fires may occur frequently. A global compilation of Younger Dryas fire studies [*Marlon et al.*, 2009] does not support a single major fire at the 12,900 year horizon, nor do studies from Europe [*van der Hammen and van Geel*, 2008]. The fossil black spherules occur in our samples whose radiocarbon ages range from 4463–24,694 cal BP (auxiliary material). We also found similar carbonaceous spherules in charcoal assemblages from low-intensity modern fire sites in southern

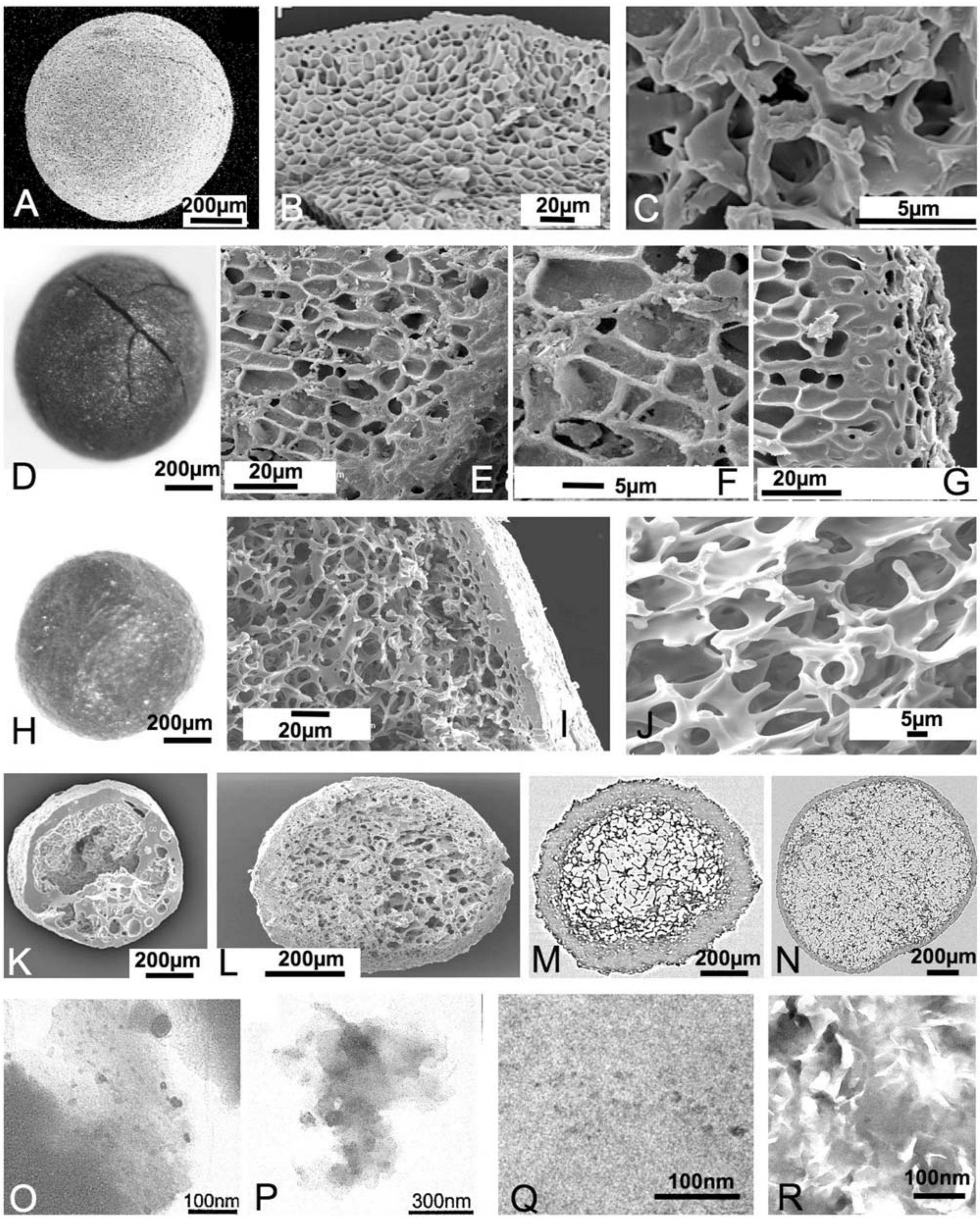

Figure 2

England (Figures 2d–2f). Typically they ranged in size from 500 μm to 2 mm (Figure 2d). In section they show a distinctive rind (up to 10 μm thick) and a cellular network of thinner walled cells (Figures 2e and 2f). These, and specimens from Santa Rosa Island, bear a striking resemblance to *Cenococcum* and *Sclerotium* (Figures 2g–2j and 2l–2n and auxiliary material).

[8] Second, charring experiments on fungal sclerotia of the genus *Sclerotium* show that they are destroyed completely at 800°C and become hollow at 550°C. Only at temperatures ≤350°C do the sclerotia retain (modified) internal structure (auxiliary material). These observations are inconsistent with the claim that spherule generation requires high-intensity or catastrophic fires as suggested by YD impact proponents.

[9] Third, when spheres are subjected to 1 hour charring at 350°C (see below), EM shows that some of the rind and cortical cells coalesce (auxiliary material). At higher temperatures (450°C), the cells thin, and voids appear in the spherules (auxiliary material) (Figures 2l–2m). In some cases the thinner-walled cortical cells form an irregular meshwork internally. SRXTM digital sections (Figures 2m and 2n) show that internal structure varies in appearance depending on the plane of section within a single sphere. Ultrastructural morphologies resembling those interpreted by *Kennett et al.* [2009b] as nanodiamonds (Figures 2o and 2p) are present in charred fungal sclerotia (Figures 2q and 2r and auxiliary material). Therefore, structure in charred fungal sclerotia mirrors that in Pleistocene spherules at mm to nm scales.

[10] Fourth, the shape of the sclerotia can vary from spherical to elongate [*Willetts*, 1969], and hence both the spherules and elongates described by *Kennett et al.* [2009a], could represent fungal sclerotia. Alternative biological origins for different morphologies include small galls (formed on plants or fungi) or insect fecal pellets. Support for these possibilities comes from the radial pattern of tissue organization (auxiliary material) and the hexagonal faceting (auxiliary material), the latter identical to that of termite fecal pellets that are frequently found in soils and are common coprolites in the fossil record [*Adams*, 1984; *Collinson*, 1990; *Scott*, 1992]. Coprolites occur commonly in many of our California samples, but from the data published, it is not possible to know what proportion of the "elongates" of *Kennett et al.* [2008, 2009b] are fungal sclerotia or coprolites.

[11] Fifth, the reflectance of organic material (vascular plants and fungi) provides quantitative data on the temperature of charring [*Scott and Glasspool*, 2007; *McParland et al.*, 2009]. We measured reflectance of fossil spherules and wood charcoal from the California study sections and reflectance of experimentally charred fungal sclerotia (auxiliary material). All fossil black carbonaceous spherules show reflectance of <2%Ro, consistent with charring temperatures of <450°C (auxiliary material). The reflectance values of the spherules are similar to those obtained from associated charcoalified wood fragments (auxiliary material). Together with the result of the charring experiments, our reflectance measurements show that the fossil spherules are unlikely to have experienced temperatures higher than 450°C. These temperatures are typical of, at most, low-intensity natural wildfires [*McParland et al.*, 2009; *Scott*, 2010].

[12] Finally, *Kennett et al.* [2008] presented 16 radiocarbon dates through the basal 5 meters of the Arlington Springs section on Santa Rosa, which we also measured, collected, and studied in detail (auxiliary material). According to these authors, all of their samples dated indistinguishably to 12,900–13,000 cal BP [*Kennett et al.*, 2008, Table 4]. These results are puzzling, given the fine-grained sediments throughout this sequence and the low-energy fluvial architecture of the deposits. In contrast, our own dating of the Arlington Canyon sequence (auxiliary material) produced continuous ages from 16,821 cal BP at its base up to the prominent dark marker bed dated to 11,467 cal BP, with several meters of additional (presumably Holocene) sediments above.

4. Conclusions

[13] *Firestone et al.* [2007] and *Kennett et al.* [2008, 2009a, 2009b] use the occurrence of carbon spherules and "elongates" and "glass-like carbon" to argue for mega-fire ignited by a catastrophic impact/airburst event at 12,900 cal BP. In reality, these materials are ubiquitous in modern environments and ancient deposits. The carbon spherules do not represent exclusive by-products of impact-triggered mega-fires as previously suggested, but rather are fungal sclerotia that are common in forest litter and soils worldwide. The so-called carbon "elongates" appear to include non-spherical forms of sclerotia and/or arthropod faecal material. Both types of material were found at multiple levels throughout our late Pleistocene to Holocene sedimentary sequences on the Northern Channel Islands of California, along with examples of the "glass-like carbon" (probably charred conifer resin preserved in sandy substrates (auxiliary material)). Furthermore the experimental charring and reflectance data pre-

Figure 2. Forms of modern and fossil carbonaceous spherules. SEMs of carbonaceous spherules and elongates from a Younger Dryas black horizon, Arlington Canyon, Santa Rosa Island, California, from *Kennett et al.* [2009b]. (a) Whole spherule. (b) Internal structure of outer part of spherule. (c) Internal structure of "elongate" specimen. Carbonaceous spherule (cf. *Cenococcum* (Figure 2g)) from charcoal assemblage after low intensity wildfire, Thursley, Surrey, 2006. (d) Light photograph of whole spherule. (e) SEM of outer part of broken spherule showing rind. (f) SEM of inner part of broken spherule. (g) Scanning Electron Micrograph of broken fungal sclerotium of *Cenococcum geophilium* showing rind, Alberta Canada. Fungal sclerotium of *Sclerotium rolfsii*. (h) Light photograph of whole slerotium charred at 350°C for 5 mins. (i) SEM of broken sclerotium showing thick rind. (j) SEM of mesh-like internal structure comprising fused fungal hyphae. (k) SEM of broken "elongate" from Arlington Canyon, illustrated by *Kennett et al.* [2009b]. Specimen shows thick outer rind and vesiculate interior. (l) SEM of internal structure of charcoalified sclerotium charred at 450°C for 5 min. Note thick rind and more vesicular interior. (m, n) SRXTM digital sections of sclerotium charred at 350°C for 5 min showing different appearance depending on the plane of section. (o) TEM of carbonaceous fragment from a powdered spherule interpreted as showing "nanodiamonds" from *Kennett et al.* [2009b]. (p) TEM of fragment interpreted as lonsdailite crystal from *Kennett et al.* [2009b]. TEM of thin sections through charred fungal sclerotium hyphal wall. (q) Dark areas similar to those shown in Figure 2o. (r) Organised area similar to that shown in Figure 2p.

sented here show that preservation of sclerotia precludes high-intensity fire and requires, at most, low-intensity burning at these sites. There is no justification to invoke high temperature impact-ignited wildfires as the mechanism for generating any of the materials reported in the YD deposits. The results here echo those of other studies that either (1) have been unable to duplicate the evidence presented in support of a YD impact [*Surovell et al.*, 2009; *Holliday and Meltzer*, 2010; *Paquay et al.*, 2009; *Haynes et al.*, 2010] or (2) have found that the impact proponents asserted catastrophic and extraterrestrial sources for material of terrestrial and/or everyday origins [*Kerr*, 2008, 2009; *Pinter and Ishman*, 2008].

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