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The Encke comet impact/airburst and the Younger Dryas Boundary: Testing the impossible hypothesis (YDIH)

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Abstract

Many have tagged the Younger Dryas Impact Hypothesis (YDIH), a supposition, lacking convincing evidence in support. The core of criticism lies squarely on uniformitarianism, that is, uniform processes moving uniformly with no room for catastrophic events, specifically cosmic catastrophic forces. Beyond philosophically based aversion to the YDIH, specific criticism comes from megafauna and archaeologic corners, related to the near coeval disappearance of specific Late Pleistocene species on the one hand, and relation to disruption and temporary disappearance of the Clovis people et al. on the other. The Younger Dryas geologic paradigm, originally in place with meltwater release into the Atlantic in tow, attention slowly drifted to explanation of an innocuous looking, thin (~1-3 cm), black sediment bed found in lacustrine and fluvial deposits of the American southwest, and other intercontinental places. Thus, with thin dark beds of Gubbio in mind, the quest to explain black mat (BM) beds took on a cosmic aspect, one with growing, supporting evidence on several continents. The impossible hypothesis, now the probable explanation of the Younger Dryas climatic reversal, is at center stage, set at 12.8 ka, with a burgeoning corpus of evidence its cornerstone.

Keywords: Black mat, Late Glacial climatic event, extraterrestrial driver

1. Introduction

As pointed out by Mangerud (2021), the Younger Dryas (YD) cold event, a reversal of insolation-forced warming following the Last Glacial Maximum (LGM) (15 ka), the Bølling-Allerød interstades of the Late Glacial (LG), went into reverse mode after 12.8 ka with a sharp shift to cold climate. The cold event itself, first recognized by Hartz & Mithersin in 1904, thereafter studied by Hartz (1912) who termed it a distinct stratigraphic clay bed, with macrofossils containing cold-loving flora consisting of *Dryas octapetala* lying between pollen identified as Allerød and Holocene-age gyttja, the latter with warmer birch macro flora; hence, the YD. The YD is 'unique' as Mangerud (2021) describes it, containing evidence for the most important climatic reversal since the LGM and likely the whole of the Neogene. It is even more unique in that the stratigraphic change was abrupt, hinging on the 12.8 ka timeline, much like the former K/T, now K/Pg, Cretaceous/Paleogene (Mesozoic/Cenozoic) timeline of 66 Ma. (Dohm et al., 2022). Moreover, unlike the K/T (K/Pg) turnover, the LG/YD boundary falls within the range of radiocarbon, offering with AMS C14, very precise timing of YD linked sediment-flora-fauna pertinent to understanding the event. More to the point, whether the YD is one of the Dansgaard-Oeschger events, an unexplained twist in insolation warming, CO_2 change, or a cosmic event, it certainly forms a most remarkable combined geochronological and time-stratigraphic time-line in Earth history. In Scandinavia, the YD, where it was first found, identified, and named, represents a sharp worldwide climatic reversal made more poignant by its close correlation with a cosmic impact/airburst.

The YD problem, originally viewed as a geological phenomenon based on pollen analysis in Norway in the early 20th Century, certainly benefitted from expanding C14; first with conventional dating, later with AMS C14, which with atom counting, improved results, and lowered the plus minus range to as little as 20–30 yr at 65% for the first standard deviation; and similar ranges with the second standard deviation at 95%. Admittedly, the pollen evidence was based on sharp contacts-warming to cooling – to which summary C14 placed the boundary at 12,737 ± 31 cal yr BP (Lohne et al., 2013, 2014), described at length by Mangerud (2021). Even from

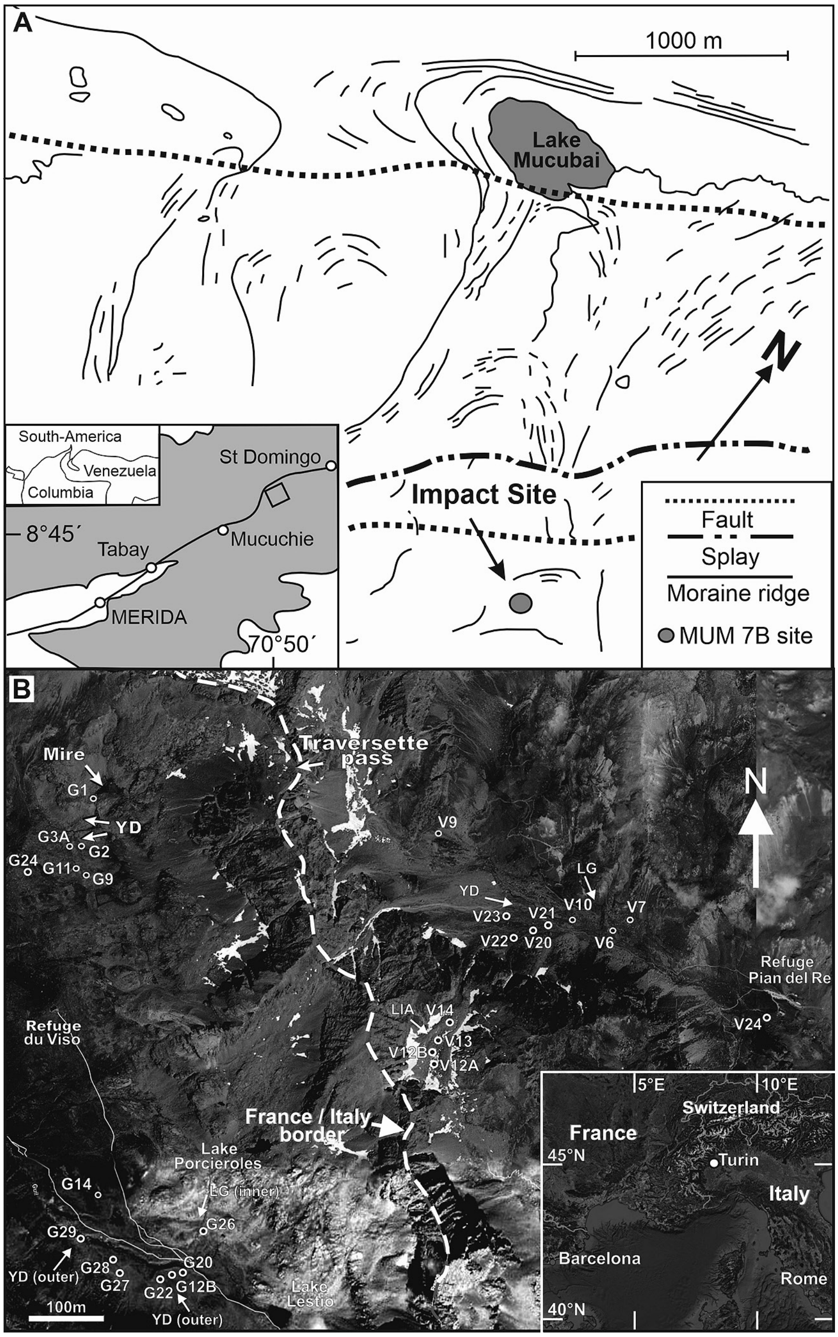

Fig. 1. A – MUM7B section, located between a LG/YD moraine stack (1) and YD recessional moraine (2) in the Mucuñuque Valley, northwestern Andes (modified from Mahaney et al., 2008); **B** – Viso Massif field area showing principal sites from Guil S to Guil N and eastward into the upper Po Valley as far as V24 near the Pian de Re Albergo at 2000 m a.s.l. (from Mahaney et al., 2022).

pollen counts, the YD was viewed as a major climatic shift. Early hypotheses relied on CO_2, variable insolation, and geohydrologic thermohaline circulation changes (Lowe et al., 2008) in the Atlantic Ocean to explain the phenomenon. A later initiative highlighted Dansgaard-Oeschger events that documented warm to cold climatic marine/atmosphere shifts, but lacking the sharp climate divide of the YD, interest quickly ebbed. Aside from considering all these hypotheses, whichever one might explain the climate shift, it had to be sudden, a complete shock to the atmosphere. Insolation was known from Bølling and Allerød pollen work to be gradual and progressive, not instantaneous as the initial YD findings indicated. CO2, as studied throughout the 20th Century was found to vary from ~270–~330 ppm, lower in glacial climates, higher in interglacials, but no clean rapid change was known from ice core or ocean records that might explain the YD climate shift. Early work with the thermohaline record involved only climate change in the North Atlantic linked to flooding from Lake Agassiz.

Ensuing work linked flooding of Lake Agassiz with melting of the Laurentide Ice Sheet at some point in the LG, possibly linked to a cosmic event. Napier (2010) linked the 2PEncke Comet-Earth encounter, occurring over the southern peripheral boundary of the Laurentide ice sheet with meltdown the possible outcome. The evidence for an impact over airburst has not been resolved because an earth crater has not been found, and possible glacial evidence has melted away with advent into the Holocene. Recently the Hiawatha Crater in NW Greenland, situated under the Greenland Ice Sheet has been proposed a possible link to the Black Mat (BM) (Kjær et al., 2018), but with an estimated Paleocene age (Kenny, 2022), only a 12.8 ka airburst is the likely cause. The 2PEncke Comet, with a diameter of ~100–200 km, is thought to have been fragmenting as it approached Earth, an airburst at some 30 km/s, powering fragments in a broad arc to the SW-ENE, each comet segment exploding instantaneously over several continents. All this is more than conjecture, as it is based on hinging together what is known against what is not actually factual – the known is the fragmenting comet and its size, earth partly covered with the Laurentide Ice Sheet, documented melting of the glacier, and meltwater flooding through the St. Lawrence and Mackenzie river systems into the North Atlantic and Arctic oceans. Early on, the YD seemed to be highly localized to one slice of the Northern Hemisphere, purely an earth-atmosphere linked event. Further studies witnessed the YD to expand in other areas far removed from the North Atlantic and the Northern Hemisphere. Sites affected by airbursts from cometary fragments yielded cosmic-affected sediment and rock/paleosol dating close to the Allerød/YD boundary. Initially, attention and interest narrowed to establish the composition of a 2–3-cm thick black (10YR 1/1) bed that looked alien to investigated stratigraphies focused on geoarchaeological problems. Aside from slipups and controversy with variable collection methods employed, sampling was tightened up (Firestone et al., 2010) by Allen West (Comet Research Group) and Rick Firestone (Lawrence Livermore Laboratory, Berkeley, Calif.) who established a protocol for collection that involved use of gloved collectors, stainless steel implements, sterilized collection bags, multiple (x12) (20 g) samples.

This latter known evidence is described and discussed below using examples from glaciofluvial sediment in the northwestern Venezuelan Andes (sites MUM7-7B sites Fig. 1A) and glacial sediment in moraines – paleosols and clast rinds – on the Viso Massif of Italy and France (G and V sites – Fig. 1B). These two occurrences combine different outcomes with the BM usually exposed as a thin black stratum in (glacio)fluvial and (glacio)lacustrine sediment, and in Greenland ice cores, against BM grains (silt-sand) fused, melted, welded, Fe-C spherule chains in clast rinds and variably distributed in paleosols (thin soils at time of airburst in the Late Allerød). Paleosol horizon materials were found (Mahaney et al., 2022) to yield high Pt/Pd ratios, often with variable Ir, Rh, and Ru concentrations many times an order of magnitude greater than crustal averages.

2. Materials and methods

Sediment at sites MUM7 and 7B (Fig. 1A) in the Andes consists of granite and granodiorite and metamorphosed-granite, a near uniform parent material which simplifies mineral and chemical analyses. The glaciofluvial sediment in site MUM7B as analyzed is nearly of a uniform clayey silt texture varying from a mixed pebbly-silty clay (Link, 1966), to coarse clastic material obtained from nearby moraine at MUM7-YD/LG. MUM7 is located 250 m north of MUM7B in the etched-in compound end moraine complex shown on Fig. 1A.

This uniform lithology in the MUM sites starkly varies from the mixed lithology of the Viso massif samples (Fig. 1B) summarized by Tricart (1984) and Tricart & Schwartz (2006), that is primarily a mixed volume of metamorphosed largely deformed marl-rich sediment, the 'schistes lustrés' group, which contributed minerals to both the Late Allerød and

YD sediments discussed here. These soft sediments carry enclosed beds of variable size including lithologies of varying resistance to weathering, beyond the deformed marl, include gabbro, basalt, meta-basalt (Tricart et al., 2003), serpentinized peridotite, and dolomite. The 'schistes lustrés' mineral zone alone consists of sedimentary and metamorphic rocks derived from Tethyan oceanic sediment, including ophiolites. The Mt. Viso and the Col de la Traversette rock suites are composed of mafic and ultramafic rocks originating from this oceanic lithosphere, that produced lithologies strongly deformed and metamorphosed under eclogitic-facies conditions (Schwartz et al., 2000). The samples were examined under the scanning electron microscope (SEM) using a ZEISS EVO MA15 SEM equipped with Oxford AZTEC-MAX energy-dispersive (EDS) system. All SEM-EDS analysis followed Mahaney (2002, 2019).

3. Results and discussion

3.1. YD climatic reversal

Aside from the pollen evidence of a grand climatic shift, perhaps the greatest of the Neogene, sedimentary evidence from the mountains of the northwestern Andes in Venezuela (Fig. 1A) and the continental divide area of the Viso Massif in Italy-France (Fig. 1B) reveals an airburst record (Mahaney, 2023; Mahaney et al., 2013b). Most BM sites are in fluvial or lacustrine sedimentary complexes or recovered ice core samples, the Viso-Andes mountain evidence the first of its kind in Late Glacial (LG) moraine sediments. What makes the Andean-Alps records important is the range of affected sedimentary complexes and the tangential landform relationships supporting the sedimentary data. In the Andean situation, the sedimentary evidence is in glaciofluvial sediment, while the tangential landform support comes into play with the main site – MUM7B – housing the evidence in between the full extent of YD ice, with a retreat phase landform marking a YD stillstand.

In the Alps (Figs 1A, 1B) the BM was identified, first in weathering rinds (Mahaney & Keiser, 2013; Mahaney et al., 2013a), later reinforced with identified soot (ash) in paleosols (Fig. 2) (Mahaney et al., 2022), identified horizons carrying grains with cosmic signatures including elevated REEs, Pt elements including Ir, Rh and Ru, elevated base metals, fused/melted/air-quenched grains, buckyball-like grains, and carbon and Fe-encrusted spherules along with carbon clusters fused in place. The weathering rind repository for cosmic evidence (Mahaney et al., 2016b) of an airburst is likely the first of its kind worldwide, and built on previous rind analysis by Nelson (1954), Sharp (1969), Mahaney (1990), Birkeland (1999) and Ricker et al. (1993), later added to by Mahaney & Schwartz (2016, 2021). Similar to the Andes, but lacking the distinct BM strata, sedimentary evidence is supported by superposed YD moraine on LG moraine in the Guil Valley of France (Fig. 3A). This contrasts with the upper Po valley of Italy where YD moraine lies adjacent to LG moraine (Fig. 3B, the YD partially eroded by fluviatile activity) (Mahaney et al., 2017a, 2022). The landform evidence clearly repre-

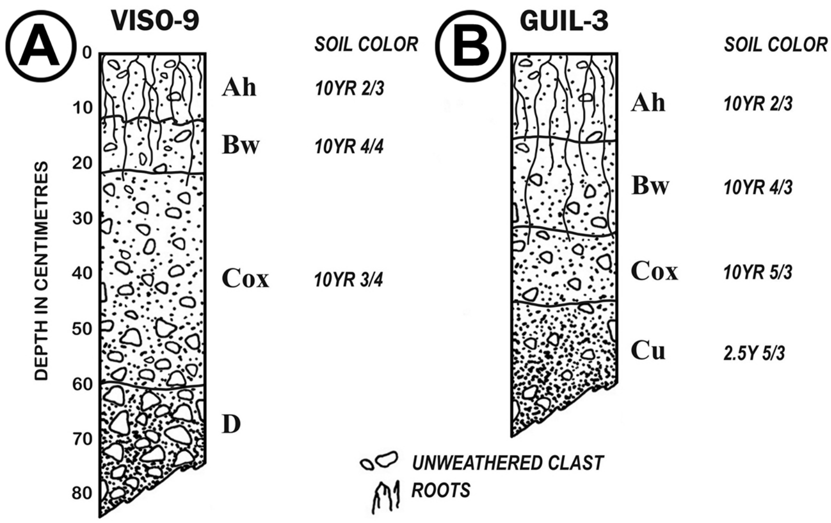

Fig. 2. Profiles in rockfall (**A** – site V9), and in moraine (**B** – site G3), from the upper Po and upper Guil valleys, respectively, with marked horizon repositories of sediment with cosmic signatures (from Mahaney et al., 2018b).

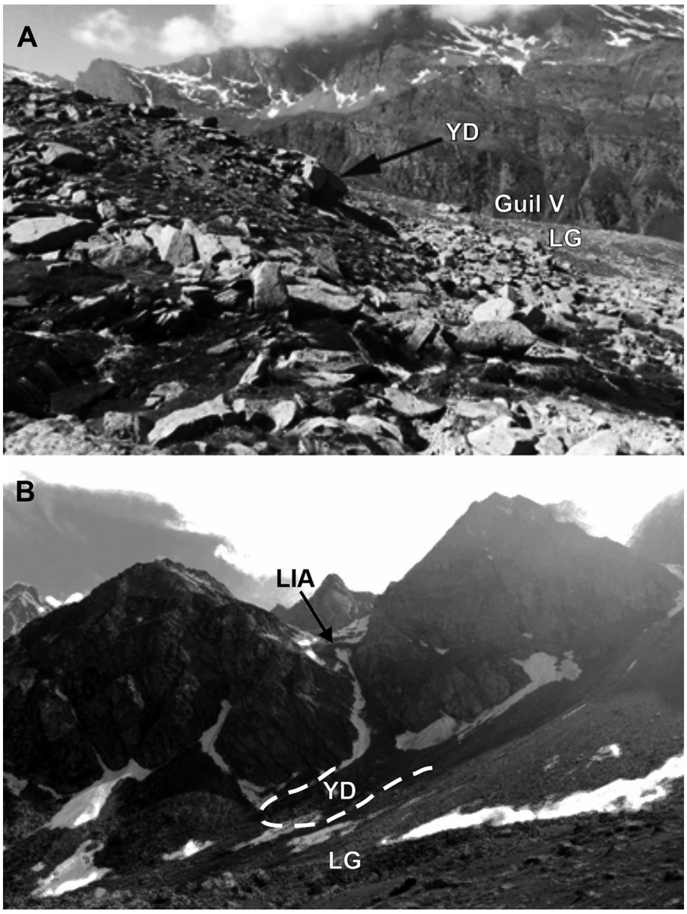

Fig. **3. A –** YD moraine superposed on LG moraine in upper Guil Valley. Thrusted clasts in the YD moraine have oriented 270° azimuths with ± 5 % variation; **B** – Image transcendental across the upper Po river showing en echelon youngest (LIA) to oldest (LG) deposits, the YD extending 150 m into the Po valley.

sents climate driven shifts in glacial mass balances during or at the end of the Allerød, such that the BM was left in place following the maximum YD resurgence and subsequent withdrawal along with at least one pause/stillstand in YD retreat. Allerød soils in these Viso surfaces, at least, are expected to have had thin, immature soils with C/Cu, A/C/Cu, A/C/R or possibly more advanced weathering of Ah/C/Cu or Ah/Cox/Cu profiles, similar to mid-Neoglacial to Late Neoglacial (Little Ice Age) proxy profiles in the Guil and Po valleys of France and Italy, as described in Mahaney et al. (2016a). For refinements of pedological terms see Mahaney (1990).

3.2. Terrestrial theory

The YD climatic divide evidence rests on pollen evidence (Hartz & Milthers, 1901; Hartz, 1912) for northern Europe, enlarged into the North Atlantic region by Lohne et al. (2013, 2014). The YD terrestrial theory rests upon meltwater drainage from Lake Agassiz, across the Great Lakes, and through the St. Lawrence River (Teller et al., 2002; Lowe et al., 2008), with later meltwater output followed the Mackenzie Catchment into the Arctic (Tarasov & Peltier, 2006). Recent research by Schiermeier & Monastersky (2010) reconstructed from meltwater terraces and reworked boulders on the Mackenzie shoreline show the intial pulse of meltwater into the Arctic coincides with the onset of the YD and YDIH at just under 13ka, or 12.8 ka. Both meltwater drainages eventually overturned the North Atlantic thermohaline circulation. Debauching vast amounts of Laurentide meltwater into the Arctic and North Atlantic oceans provided compelling arguments for climate change at the end of the last ice age, but with considerable lag time and only regional outreach. Once the YD was seen to be a climate reversal on a worldwide scale, even reaching the Antarctic, workers searching for more terrestrial forces (causes) turned to CO_2, solar activity Kudryavtsev & Dergachev (2021) and marine overturning of the Atlantic Current (Broecker et al., 2010)

Virtually out of the blue, Firestone et al. (2007a, 2007b, 2010) coupled cosmic-affected sediment with the YD climate reversal, and all this, on an intercontinental basis. Workers on the terrestrial side brought forth the Dansgaard-Oeschger theory linked to marine-geohydrologic coupling thought to occur at the end of glaciations. The meltwater discharge and marine current thermohaline change have been well established by several workers: the St. Lawrence (Teller et al., 2002) and the Mackenzie by Tarasov & Peltier (2006). However, recession of the Laurentide Ice Sheet (LIS) through southern Manitoba by Gauthier et al. (2022) challenges meltwater volumes released through the Mackenzie system and shows LIS terminal limits during the Late Glacial indicating the 2PEncke impact/airburst might have occurred over stagnant or thin recessional ice of unknown thickness and occasionally with terminal moraines just north of the US/Canada border.

Gauthier et al. (2022) also discuss some of the outstanding questions relative to the YD, namely drainage to the St. Lawrence (Broecker et al., 1989; Carlson et al., 2007; Leydet et al., 2018), triggering YD cooling backed up with drainage through the Mackenzie to the Arctic (Tarasov & Peltier, 2006; Keigwin et al., 2018), adding to the St. Lawrence input to the N. Atlantic Ocean. Modeling (Norris et al., 2021), supports drainage as hypothesized previously, but as Gauthier et al. (2022) state "unambiguous evidence of Lake Agassiz water or sediments connected to drainage does not exist" and others (Fisher & Lowell, 2012; Voytek et al., 2012), some with a change of mind (Broecker et al., 2010), challenge both hypotheses. Even with these longstanding hypotheses, and more recent adjustments, it seems meltwater debauched into both the N. Atlantic and the Arctic Ocean, occurring with variable volumes and over varying time limits.

The uncertainty of placement and timing of LIS glacial lobe withdrawal along the US/Canada border, especially in southern Manitoba, is critical to calculations of meltwater withdrawal from Lake Agassiz (Fig. 4A), as originally stated by Leverington et al. (2000). Variable interpretations of ice margin position and lack of age control combine to make estimates of meltwater discharge uncertain. However, an OSL date of 14.3 ± 0.3 ka marks the initiation of Lake Agassiz when the Red River Lobe retreated north of the Bigstone Moraine (Lepper et al., 2011, 2013). Tentatively, the Red River Lobe's margin is placed off the Tiger Hills marking impounded Glacial Lake Hind in SW Manitoba with an age of 13.0 ka cal BP (Fig. 4B), based on two AMS C14 ages (Fig. 6 and Table 1 in Gauthier et al., 2022). This average age is important because it suggests Lake Agassiz was not able to debauch meltwater to the NW at the start of the YD, and further, because the LIS ice margin was located 80 km SW of a previously quoted 12.8 ka cal BP ice margin shown in Fig. 2 of Dalton et al. (2020). Admittedly, this assessment, based on limited C14, varies from previous work by

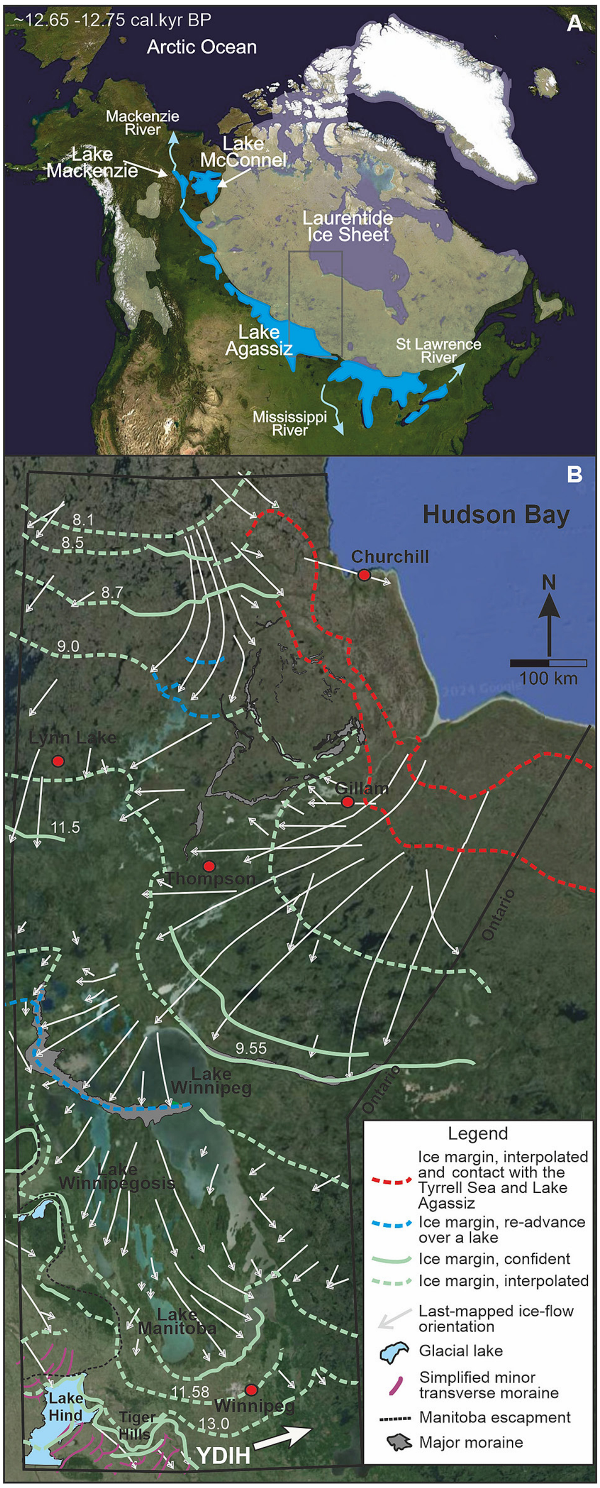

Fig. 4. A – Initial deglaciation of the LIS and growth of Lake Agassiz, initiation of drainage through the St. Lawrence and Mackenzie sluiceways, at or about the time of random 2PEncke fragmental encounters elsewhere on intercontinental surfaces. Rectangular marked area delimits area enlarged in B; **B** – Deglaciation of Manitoba showing position/ages of key moraines, the YDIH, if it occurred, centers around the ~13 ka moraine near the Canada/US border (after Gauthier et al., 2022).

Teller et al. (2020) and others and will probably require additional work using LIDAR. The equivocal dating of ice margins in southern Manitoba needs to be upgraded before we can establish firm time lines before and after the YD climatic divide.

Disgorging vast amounts of meltwater into the Atlantic and Arctic oceans, even over variable time lines, would have affected the thermohaline current, warm salt water sinking, the surface becoming demonstrably colder, sufficient according to Lowe et al. (2008) to answer the question of the YD climate change; but was it abrupt as every other line of evidence asserts? It is the abruptness of the YD climate divide that flies in the face of uniformitarianism (Powell, 2023); if it is terrestrial it has to be unique, perhaps as earth shattering as for example, earthquakes. More to the point, the YD climate divide cause has to be sufficiently forceful to overcome insolation heating ongoing since the LGM/Bølling turnover (Thiagarajan et al., 2014).

3.3. Cosmic theory

Earth encounters and comet fragmentation (breakup), first described by Napier (2010) have become more technically astute (Napier, 2019), as specified in the Monthly Notices of the Royal Astronomical Society, which provide new details. As well, main belt asteroids that may provide a possible YD impactor (Usatov, 2020) have yet to be identified. As noted by Napier (2019), Earth's encounter with 2PEncke would take the form of an intense meteor hurricane lasting a few days, putting enough dust in the mesosphere to block sunlight for settling time of at least a few years along with enough fireballs to create a global wildfire (documented by Wolbach et al., 2018a, 2018b). Such has been reported (Senel et al., 2023) from the Tanis Site in N. Dakota where paleoclimate simulations from the Chicxulub impact put 0.8–8 μm dust in the global atmosphere for up to 15 yr. causing ~15°C drop in world temperature. Whereas 2PEncke would have produced silicate dust for the most part accompanied by soot, Chicxulub added measurable sulfur creating acid rain doubling the killing aspect of the K-Pg boundary.

At the time of the YDB, Comet 2PEncke was uniquely placed to cause damage: it was almost in the orbital plane of the Earth while simultaneously intersecting Earth's orbit (paper submitted). The effects of passing through 2PEncke's trail would have been global. And while 2PEncke is estimated to have had a diameter of ~100 km or more (Napier, 2019) its velocity was presumably in the range of ~30 km/s; its structure small compared with other rogue comets possessing diameters well in excess of Earth's diameter ~12,756 km. 2PEncke's collision with the southern perimeter of the LIS (Laurentide Ice Sheet), if an impact, would have built a crater of unknown depth in ice; if an airburst the collision would have melted ice to an unknown, if lesser depth. In either case the collision melted enough ice to build escape channels to the east into the North Atlantic and northwest along the Mackenzie River to the Arctic (Fig. 4A). Further, what if the comet trail's impact with Earth produced an enormous cloud of dust reaching to the upper atmosphere, with particles the diameter of aerosols (approximately the ~1–6–8 μm size of normal clay-fine silt minerals), were to become resident in or near the exosphere (~700–10,000 km)? In its lowermost zone – the tropopause – the atmosphere enters space and where dust particles below might take decades/centuries to return to Earth, the area above with declining pressure, dust may linger far longer than following the explosion of Krakatoa in the 1880's. Even the stratosphere, with its temperature inversion, held dust from Krakatoa, which led to its naming by L.T. de Bort in 1902. Above the stratosphere (~50 km), and within the exosphere, there is no barometric pressure to encourage particles to move within wind systems and gravitational forces are minimal; hence dust (think diamond dust of Fred Hoyle; Napier, personal correspondence, 2023), might help prolong the YD once the heat and pressure of the initial airburst/impact subsided. Recent work with dust and greenhouse effects (Kok et al., 2023) argue that increased dust production in the atmosphere over the last century have lessened greenhouse warming.

Following Firestone et al. (2007a, 2007b, 2010) release of cosmic signatures on sediment in several early sites investigated by others, old sites were reinvestigated and new ones followed, several per year. Chief among the mix of old and new sites include the seminal works of Kennett et al. (2007, 2009), LeCompte et al. (2012), Israde-Alcántara et al. (2012) and Wittke et al. (2013), followed by Goodyear et al. (2015), Kennett et al. (2015) and Andronikov et al. (2016), which along with Kinzie et al. (2014) laid the ground-truthing that led to the 12.8 ka isochronous age for black mat sediment on an intercontinental basis. This research accompanied other findings in Peru by Ge et al. (2009), Belgium by Kloosterman (2015), in Greenland by Petaev et al. (2013), Antarctica by Mahaney et al. (2018a), South Africa by Thackeray (2019), in Chile by Pino et al. (2019), in Manitoba by Teller et al. (2019), Moore et al. (2020), in the Atacama by Schultz et al. (2021), and in Jordan by Bunch et al. (2022), linked, as usual, with deniers of BM sampling sites and isochronous dating controls between sites. Principal among the deniers is reproducible dating evidence at key sites, brought forth and itemized by Surovell et al. (2009), reiterated by Carlson et al. (2007), Holliday et al. (2014), Meltzer et al. (2014), Van der Hammen & Van Geel (2008) and reinforcement of the terrestrial hypothesis by Broecker et al. (2010). Such criticism was soon refuted by Kennett et al. (2015) who used Bayesian analysis to prove synchronous ages for black mat sediment of 12,835–12,735 cal BP for the Younger Dryas boundary on four continents. Following the 120-kyr record of biomass burning events which focused on the BM by Wolbach et al. (2018a, 2018b), Holiday et al. (2019) followed with a full discussion as to why biomass burning did not require a cosmic source and why the black mat event was unrelated to the disappearance of the megafauna and the Clovis Culture. Such criticism was fully refuted by Wolbach et al. (2019) and discussed in full by Sweatman (2024) who focussed on fallacious interpretation of BM AMS C^{14} age controls by Holliday et al. (2023). A more recent article denying the black mat (Holiday et al., 2023, in preprint form), cites a litany of old arguments critical of a cosmic cause, mainly focused on sampling techniques and critical of AMS C^{14} dating of relevant sites, all of which was dealt with by Wolbach et al. (2019). Interesting that this recent criticism of Holiday et al. fails to cite (Mahaney, 2023) and Mahaney & Somelar (2023, preprint in Sci Report) that lay open the astronomical evidence of Earth interacting with the 2PEncke Comet Trail releasing multiple intercontinental airbursts wreaking havoc across the planet, pole to pole. Beyond this, no mention is made of atmospheric effects that for an unknown time would have affected the highest reaches of the air column reaching 50 km (upper stratosphere/stratopause) and beyond, producing a nuclear winter. Assuming terrestrial evidence for termination of the YD (Mangerud, 2021)), the nuclear winter event as postulated by the YDIH would last 1.4 kyr.

Curious still, the cause and effect evidence offered from AMSC14, the megaton airburst pattern coming in at 12.8 ka was followed by pollen evidence fixing climatic cooling at 12.7 ka, with decades to spare. Moreover, the main cosmic driver of the YD, relegates the former marine thermohaline cause to that of a secondary supporting role which in any case might have taken centuries to produce the YD climate change. While this is a short summary of black mat deniers piercing the literature with criticisms, it seems no matter how many new black mat sites are found and investigated, no end of rebuttals follow, mostly with archaeological or anthropological end notes that are all terrestrial and fail to accept any cosmic connotation.

The lingering burnout event of a vast swath of Siberia (1908) defied explanation, not one scientific authority centering on either a terrestrial or cosmic cause, until Svetsov (1996) showed evidence for an irrefutable cosmic connection. The vehicle – asteroid or comet – remains to be proved, but cosmic is firmly in place.

3.4. Correlation to mountain sites

The Andean discovery of the 2–3 cm-thick black strata in glaciofluvial sediment of the Mucuñuque Valley goes back to the 1990's, initially a puzzling encounter, later outlined in Mahaney et al. (2008), at the time ascribed to lightning. Despite environmental interpretations arguing against lightning strikes, mainly the wet seral stage of a developing tundra, lightning ignition seemed to be the only answer. Later with the seminal finds of Firestone and associates (Firestone et al., 2007a, 2007b, 2010), aligned with our detailed investigations showing melted/welded/air-quenched grains of different lithologies along with carbon and Fe spherules, some affected sediment fused with Pt, specifically with Ir concentrations reaching many orders of magnitude higher than crustal average, opened a cosmic window to explaining the YD.

Originally only one mountain BM site was known from work at MUM7B in the northwestern Andes; however, new recent evidence has been found in the European Alps (Mahaney et al., 2013b; Mahaney & Keiser, 2013), specifically in the Mount Viso area astride the Italian/French continental divide. Glacial landform investigations and analysis of weathering rinds and paleosols led to discovery of melted/welded grains, fused clusters of opaque carbon masses, and air-quenched grains in recovered sands, all of which paralleled findings at MUM7B in the NW Andes. The onset of glacial mapping led to further research on the YDIH, with continual investigations yielding melted, welded and air-quenched minerals, fused in clastic rinds (Fig. 5 for example) embedded in paleosol covers in LG moraines. Similar evidence was recovered in sediment of YD moraines, with the final summary of sites identified in Mahaney et al. (2022; Figs 1 and 2). The effect of pressure and heat waves on rock (i.e. clastic rinds), annotated on a rind from site G3A (site on Fig. 1B), illustrates a shocked-granulated rind surface later invaded by lichen (Fig. 5). In the case of Fig. 5, mineral surfaces include amphibole

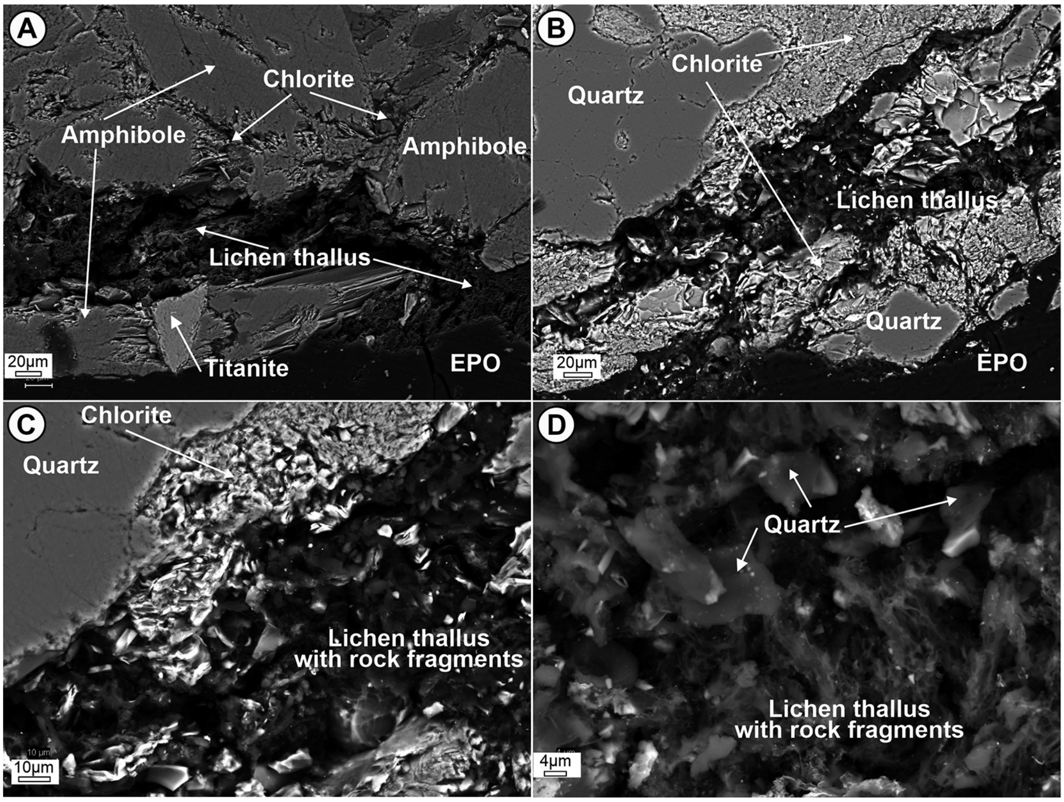

Fig. 5. Clast serpentine rind from site G3A (KVx OA 8), showing partly shattered rind edge abutting cement (EPO), with a mechanically cracked lichen-filled area in **A** across the lower frame image. The lichen is probably a species of *Rhizocarpon* or *Lecanora*, common in the Western Alps. In places, tonal contrasts suggest lichen thalli absorption to rock (in **D**), especially related to uptake of Fe for respiration. Shear planes, perpendicular and normal to PT forces, cover the rind to an internal thickness of ~200 µm, many filled with melted/welded particles.

and quartz, greater mineral breakup in the former, less in the latter. Some subparallel and conchoidal fractures might be glacial, but with a sphene (titanite) shear zone, fractures to the right may be shockwave induced. Iridium, rarely detected by EDS assay of sand coatings recovered from paleosols, measured by fire assay of samples from some 80 horizons of 21 sites, revealed concentrations at several orders of magnitude above crustal average (Rudnick & Gao, 2005). Opaque carbon masses, often fused within tightly formed groups of minerals or crystals, lie arranged in phalanx-like structures. Those mineral masses are rearranged and reoriented due to pressure within rinds, shifting several hundred microns toward internal rock cores as illustrated by Mahaney et al. (2016b). These masses, often associated with Fe and carbon spherules, sometimes interlaced in necklace form, are considered to be the product of heat above 2000°C and pressure of several hundred atmospheres. It is this interlinked clast rind-paleosol record, age determined by relative dating (RD) methods to within ± 300 yr of the Allerød/YD climatic divide, and fixed by AMS C14 at 12.8 ka by Kennett et al. (2015), that support the YDIH. The BM discovery at the MUM7B site in the northwestern Andes was quickly shown to be the product of an airburst (Mahaney et al., 2013b), any link to volcanism considered remote, and its link to YD glacial advance and retreat stratigraphically fixed at 12.8 ka by AMS C14 (Mahaney, 2023). Moreover, the Andean and Western Alps records alone provide an intercontinental correlation sufficient to embed MUM7B (NW Andes) as an informal type section under the American Commission Stratigraphic Nomenclature, previously suggested by Mahaney (2023).

3.5. Linkage of terrestrial and cosmic theories

Considering the scope of the 2PEncke comet airburst and resultant BM signatures in nearly a worldwide setting pole to pole, the missing crater has resulted in fallback on an airburst that could be compared with the fallout from the Chicxulub event of 66 Ma, which left a crater compared with Gale Crater on Mars (Dohm et al., 2022) with planetary fallout on a planet-wide basis. Considering the variation in impact timing of the K/T (K/Pg) on Earth for Chicxulub, coupled with the Noachian (~4 Ga) for Gale Crater on Mars, considerable loss of material has occurred in post-event time. Whereas for the 2PEncke Event of 12.8 ka considerable evidence remains to reconstruct postglacial environmental change with unparalleled accuracy. Moreover, despite BM deniers, it is now possible with unprecedented AMS C14 accuracy to date LG/YD pollen sections in Europe to 12,820 cal yr BP with two sigma uncertainty of ~100 yr (Engels et al., 2022), the wider spread of European pollen sites slightly advancing the earlier mean age of 12,737 ± 31 cal yr BP from Krakenes, Norway (Lohne et al., 2013, 2014) and black mat sites worldwide at 12.8 ka (Kennett et al., 2015). This explains the connectiveness of the 2PEncke Airburst of 12.8 ka with the fallout result of a pollen shift trailing by decades to 12.7 ka. Despite the lack of AMS C14 controls to accurately time the release of meltwater from the LIS to the N. Atlantic and Arctic oceans, it is reasonable to assume the thermohaline turnover must follow along during or about 12.7 ka. At the very least, the 12.8 to 12.7 ka fallout suggests cause and effect; the airbursts sending dust into the atmosphere, producing a nuclear winter; following on-daughter-fragment airbursts generating black mat sites worldwide, the effect changing the climate as registered by the pollen anomaly of *Dryas octapetala*. Instead of the meltwater discharge from the LIS producing the registered geohydrological thermohaline turnover and the YD climate divide as one cause and effect, with the scenario presented here, it becomes the 2PEncke fragment fallout force that set YD cooling for the larger worldwide atmosphere. Hence, the impossible hypothesis YDIH even with diverse criticism coming from distant quarters, much of it led by Holliday et al. (2019), becomes the most probable, if not possible answer explaining the YD climatic divide. Thus, the stage is set for merging two competing theories of climate change, perhaps a coupling of cosmic and terrestrial into one paradigm of cause and effect.

3.6. Younger Dryas significance

The YD Climatic Divide may well prove to be more than just a shift in climate following the last glaciation, it may be a funnel through which human genetics formed (Heaton, 2022) onside the elevation of words in the human genome (Rassokha, 2020). Beyond these attributes, if the main 2PEncke airburst produced the YD climatic shift as postulated, it would have produced a short-term burning event followed by a nuclear winter, an event capable of cooling much of the Earth's surface with a dust-produced cooling climate for an unknown period of time. As summarized by Wolbach et al. (2018a, 2018b) in the 120-kyr worldwide fire record, sedimentary evidence shows such an event occurred approximately 12.8 ka, supporting such a cooling event. Heaton's (2022) decline in human population coincides with depopulation of the Clovis Culture in North America and loss of megafauna almost at the same time, co-incidental events that are hardly, simply coincidently linked, lacking cause and effect. AMS C14 dating alone places the Earth/2PEncke collision as cause of the sharp YD Climatic Divide indicated from pollen trends (Mangerud, 2021), and δ18O Greenland curves (NGRIP) of Svensson et al. (2008), followed by regional reinforcing mechanisms such as meltwater drainage into the North Atlantic and thermohaline marine cooling and dust-effected atmospheric cooling. The YD cooling measured from pollen recovered from the Krakenes Lake Core, reported by Mangerud (2021) yields start up YD AMS C14 age of 12,737 ± 31 cal yr BP well within the slightly older 12.8 ka age of worldwide black mat sites. The BM came first, the pollen later, separated by decades given the latest pollen evidence (Engels et al., 2022).

In the face of postulated astronomic-terrestrial linked occurrences, the impossible YDIH hypothesis is fast becoming a principle paradigm to explain the YD Climate Divide, no different than the K/T Chicxulub Event that terminated the Cretaceous. Missing a crater, the 2PEncke airburst event is projected to have set in motion YD cooling at 12.8 ka (Kennett et al., 2015), reinforced by cooling of the thermohaline current in the N. Atlantic, dust loading of the atmosphere at different altitudes, and Earth's frequent encounter with Taurid meteor hangovers (daughter event fragments) lingering in Earth's orbit. If pollen-dated beds at Krakenes are correct the YD Climatic Divide terminated 11,535 ± 58 cal yrs BP (Mangerud, 2021).

4. Conclusions

Early postulated terrestrial hypotheses to explain the YD climatic shift are understandable, given the long history of uniformitarianism (Lyell, 1830–33) in geology and geomorphology, and reluctance among some to entertain catastrophic hypotheses as viable causal earth-shaking occurrences. Despite indisputable craters on Earth, Chicxulub among them, the lack of an identifiable crater linked to the black mat reduces the Younger Dryas Boundary (YDB) to an airburst event that left only partial melting of the Laurentide Ice Sheet as evidence. To invoke Lake Agassiz drainage and its effect on the thermohaline circulation of the North Atlantic Ocean as the prime driver of the YD climatic shift, is to limit the size of the affected area to a single region. With YD evidence findings worldwide, the scope of the YD evinces a more suitable explanation, one which couples the C14 dated pollen evidence from Norway with an atmospheric disruption suitable to explain intercontinental occurrences. Multiple AMS C14 ages on Norwegian pollen evidence set the terrestrial timing at 12,737 ± 31 cal yr BP (Lohne et al., 2013, 2014) ka for the climatic shift, decades younger than the established impact/airburst timing of the Laurentide meltdown with consistent synchronous ages of 12,835–12,735 cal BP; hence, 12.8 ka is a firm average age for deposition of black mat sediment worldwide (Kennett et al., 2015), and hence, for the YDIH hypothesis.

The timing of the impact/airburst as cause with the pollen evidenced climatic shift as effect are hardly coincidental.

Coincidental cosmic and terrestrial occurrences do not confirm cause and effect exactly but they do allow a measure of undeniable evidence, against other forces, agencies such as Dansgaard-Oeschger events linked to geohydrologic marine events, an unexplained twist in insolation warming, or CO_2 variations. Even the pollen and ice core evidence indicate an abrupt climatic shift which eliminates geohydrologic-marine events and CO_2, leaving cosmic the driver, all geohydrologic lag changes as reinforcer agents prolonging YD time, with CO_2 relatively unchanged. An insolation abruption lingers as an unknown force. When considering the YDIH hypothesis slowly gaining strength and interest with the finding of new sites, it is well to consider the ill-received glacial hypothesis of Agassiz in the 19th Century; and the continental drift hypothesis of Alfred Wegener in the early 20th Century, expanded later to the plate hypothesis of Harry Hess, Maurice Ewing and Bruce Heezen in mid-century. The shift to glacial movement and moving continents started with denial, then possible acceptance, and finally a realization that all knew the hypotheses were correct all along. With the black mat we are in a stage of growing acceptance, each new site moving the scale to full acceptance. The twin dating – cosmic to pollen – for sediments right at the Younger Dryas Boundary is tentatively, almost begging, full acceptance, especially since other contenders – geohydrologic forces, thermohaline ocean shift, CO_2, break of insolation heating – are either too slow to achieve a climate abrupt shift, or are unknown in Earth history.

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Data availability. This research is the product of work carried out previously over several decades and the data reside in my lab files and computer hard drives, accessible to all at any time via <arkose41@gmail.com>. Some published data reside in www.billmahaney.com

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