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Critical assessment of Jenny's soil forming equation in light of cosmic airbursts on the Viso Massif

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Abstract

Jenny's soil formation equation places soil morphogenesis as a response to climate (cl), biota (o), relief (r), parent material (p), and time (t), written thus: s= *f* (cl, o, r, p, t…), where each variable is considered independent. Because some soils and paleosols contain cosmic impact/airburst evidence, recent soil morphogenesis research requires a rewritten equation: s= *f* (cl, o, r, p, t, **c**…**)**, where c = cosmic. This addition serves to alert researchers to the presence of cosmic input to soils under investigation as part of geological and geomorphological projects. In particular, research targeting the cause of the Younger Dryas Climatic Divide (YDCD) might focus only on pollen in European glaciolacustrine sediments, reversal of the marine thermohaline circulation in the N. Atlantic Ocean, and possible reversal of postglacial warming at the Allerød termination (12.8 ka), when a search for cosmic grains may change the research outcome. Hence, the importance of the 'c' addition to Jenny's factor analysis of soil morphogenesis.

Keywords: Soil morphogenesis, France/Italy borderland, cosmic injections to soil genesis, 'c' independent soil forming variable

1. Introduction

The proposal to introduce 'c' into Jenny's soil-forming equation came about fortuitously, first, during investigations of a classics-geoarchaeological problem related to Hannibal's invasion of Italia (Mahaney et al., 2017a); second, during an investigation of a glacial-soil sequence around the Viso Massif (Mahaney et al., 2016a) (Figs. 1, 2) along the France/Italian Continental Divide; and third, to combined microscopic investigations of sands and rinds, which indicated an unexpected cosmic event (Mahaney & Keiser, 2013). While younger Holocene deposits were dated by AMS C14 (Mahaney et al., 2018b), no obtainable materials were recovered to date moraine and mass-wasted deposits laid down in the Late Glacial (LG) and Younger Dryas (YD). Therefore, most deposits were subject to dating by relative dating (RD) methods that rely on topographic position, lichen cover, weathering rind development, and overall soil/paleosol expression (Mahaney et al., 2016a). Such deposits were designated Allerød in age based on their position in the glacial retreat phase placed in juxtaposition to superposed YD-age deposits (see examples in Figs 3a and 3b in Mahaney et al. 2022).

Taking soil-forming factors into account (originally integrated by Dokuchaev, 1883), revived by Jenny (1941) and integrated into Quaternary geology by Birkeland (1999), chronosequences with a proposed cosmic input rely on s = *f* (cl, o, r, p, t, **c**), where 's' is the soil system, *f* the functional relationship, and cl (climate), o (biota), r (relief), p (parent material), t (time), and **c** (cosmic airburst). These

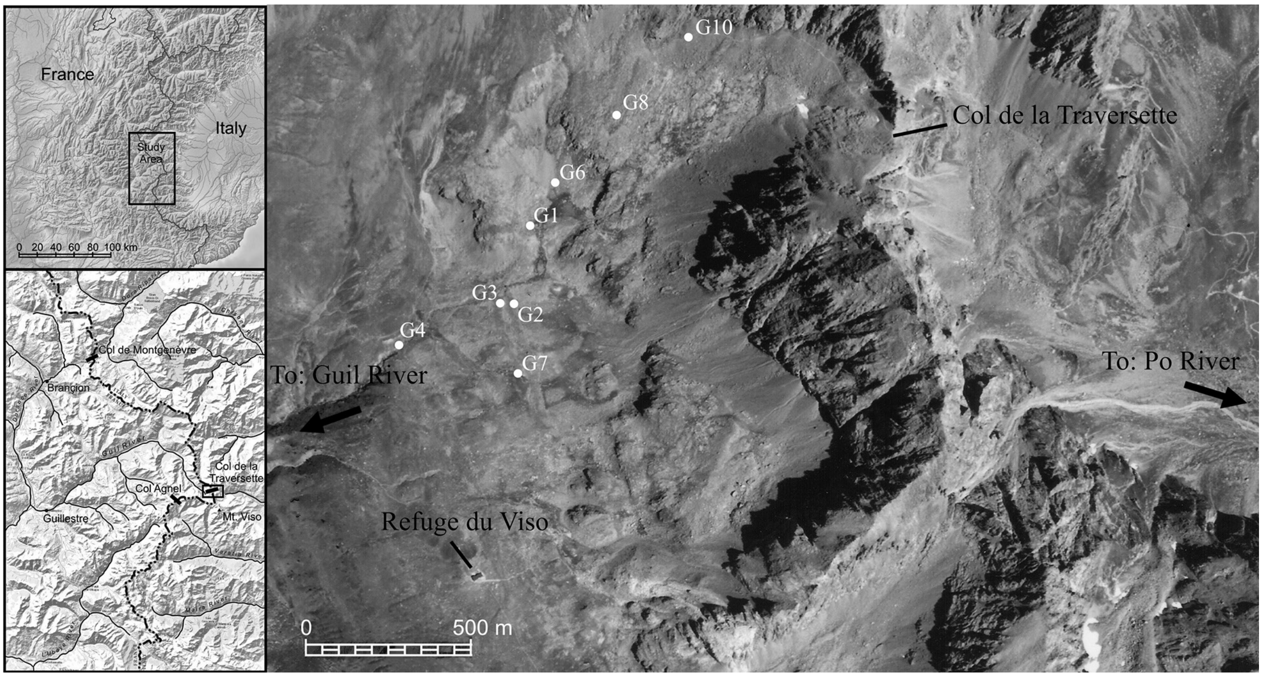

Fig. 1. Sites in the upper Guil catchment, France. Sites G1 and G2 follow the inner moraine ridge. Site G3, one of the most active cosmogenic sites on the Viso Massif, contains the full effect-clast rind to paleosol of an airburst (Mahaney et al., 2016a).

all are considered independent and semi-dependent variables. To discuss (▲s=▲t)cl,o,r,p,**c** (dt), the time factor becomes a partial derivative of the ratio (ds/dt); hence, one is forced to select sites where time is variable or relatively so (e.g., on ridge crests or depressions) and with uniform parent material, as determined by mineral or chemical criteria. In calculating climate (cl), most workers use macroclimate data from the weather service when, in fact, depending upon 'r', slope factors may determine changes in macro or microclimate. Additionally, biota (o) responds to changes in microclimate, which is why all three factors – r, cl, and o – need to be established so that all three are kept as semi-dependent variables. In this instance, the main independent variable is time (t), with minor slope (r), a semi-dependent variable controlling uniform site topography. Add to this a cosmic airburst (**c**), as represented by the Younger Dryas boundary layers (YDB), often called the 'black mat,' that has been dated to 12.8 ka at the Younger Dryas onset (Kennett et al., 2015), a cosmic event that produced a widespread conflagration with wildfires generated over intercontinental areas (Wolbach et al., 2018a, 2018b). The 'black mat' is the term used here to denote the Younger Dryas boundary layer (YDB), or YD Climate Divide (YDCD) defined as a thin (2–5 cm) black (color=10YR 1/1) sedimentary bed, whose origin is typically within fluvial, lacustrine (Mahaney et al., 2013a), or in ice cores from Greenland-Antarctic (Mahaney et al., 2018a). The classic YDB black mat, a thin 2–5 cm-thick bed, is not present in the Alps where similar cosmic evidence is found widely distributed in rock rinds and paleosols. Instead, the black mat, as discussed below on the Viso Massif, refers only to altered, carbon-enriched, welded/melted grains, either in rinds or sands-silts encrusted in paleosols to various horizons and depths (Mahaney et al., 2013b). Thus, the distinctive 'mat' is elusive in high-altitude areas of the European Alps (Mahaney et al., 2022), most likely because lacustrine sediments are rare in this area.

The introduction of '**c**' into the soil-forming equation becomes doubly important when one considers the effect of cosmogenic input into immature soils of Allerød age evolving into paleosols, such that, in addition to in situ mineralogy, cosmogenic airbursts/impacts add new allochthonous minerals and chemistries to the environmental mix. While we do not know the exact pressure and temperature exerted by a fragmental airburst over the Viso Massif, we can estimate by the reduced area affected compared to Tunguska (Svetsov, 1996), pressure was probably <300 kPa with temperature >2000°C. Quartz crystallizes from magma at ~650°C but pure quartz at 1 atm melts at 1700°C; 1670°C for B-tridymite, 1713°C for B-crystobalite (Deer et al., 1966). A cosmic event brings not only pressure/temperature (P/T) forces to bear, such that pressures in the kPa range and temperatures ≥2000°C for impacts and airbursts can physically affect clastic sediments, melt minerals, and combust exposed vegetation. Physical manifestations of airbursts are most easily seen in rock rinds (Mahaney et al., 2016b), where shock waves intruded hundreds of micrometers inward, after which shock release left rock masses more easily penetrated by subsequent fluid invasion during normal climatic changes. Such shock causes high-T-melting of grains in rinds along with combusted carbon as opaque masses, often infused with a variable mix of mineral oxides.

The influence of 'c' upon 'o', that is, microbial communities evolving and disrupted by P/T forces has yet to be worked out on metagenomic levels, but new information suggests proposing that P/T forces from cosmic encounters may influence DNA in evolving bacteria. Denaturing Gradient Gel Electrophoresis (DGGE) analysis, a molecular fingerprinting method, separates polymerase chain reaction (PCR)-generated DNA species providing templates of DNA sequences representing the dominant microbial organisms in a soil system. The analysis of 16 samples in the upper Guil catchment (France) indicates one instance (Site G3, Fig. 1) where a genetic indicator suggested a variant bacterial strain that might link the airburst to evolution pathways (Mahaney et al., 2013a). Thus, with 'c' identified at any YD site, the problem widens from analysis of 'p' to separate normal weathering of in situ mineral material and to probe for cosmic biosignatures such as air-quenched, shock melted, and welded grains to chemical identifiers such as Pt/Pd ratios discoverable by INAA and fire assay analysis to establish Pt element (Os, Ir, Ru, Rh) concentrations and distributions in paleosols, such as in Mahaney (2023) and Mahaney et al. (2022). In addition, as shown in these publications, analysis of REEs, elevated base metals such as Fe, Co, Cr, Cu, may align with Pt elements and REEs, especially the HREEs (Mahaney, 2023).

New cosmic sites are being frequently proposed (Svetsov, 1996; Mahaney et al., 2013a, b; 2016a; 2018a; Wittke et al., 2013; West & Firestone, 2013; Moore et al., 2017; Wolbach et al., 2018a, 2018b; Tankersley et al., 2021; Bunch, 2022; Powell, 2022). The problem is how to fit such 'catastrophes' into Jenny's soil-forming equation to bring a cosmic effect 'c' into the equation. A bigger problem, perhaps, is to calculate 'c's effect on other independent variables from Allerød soils that later evolved into paleosols.

The Viso Massif (France-Italy) is a prime laboratory to work out pathways of adjustments to each independent variable in Jenny's equation. At the site, the YDB impact event has now been identified as an isochronous timeline in which the onset of the Younger Dryas (YD) episode, one of the greatest climatic shifts of the Late Neogene, is fixed at 12.8 ka by Kennett et al. (2015) and Mahaney (2023). This timeline of 12.8 ka matches the YD chron of Mangerud (2021) based on pollen evidence from Kråkenes, Norway. Additionally, as discussed by Mahaney (2023), evolving pollen databases show that pollen changes follow within decades of the YDB cosmic timeline of 12.8 ka established by Kennett et al. (2015) supporting a paradigm of a cosmic cause for the YD, followed in turn by pollen downturns in temperature and marine thermohaline current changes. Establishing cause and effect for the YD requires only rational analysis of the evidence.

2. Materials and methods

Materials and methods are fully described and discussed in Mahaney et al. (2013a, 2016a, 2022). All classification follows mostly the NSSC (National Soil Survey Center, 1995) with the 'h' in Ah, a variation from the Canadian Soil Taxonomy System (1998). The 'ox' horizon identifier for oxidation comes from Birkeland (1999) and is used to identify oxidation strength in C horizons. The Cu (u=unweathered) designation originated with Hodgson (1976). Samples were studied by LM (light microscopy) using a Leica SA080 LM. Clast samples and sands were analyzed by SEM following methods outlined in Mahaney (2002).

3. Results and Discussion

3.1. Glacial geology – Viso Massif (Italy/France) case study

The full extent of LG and YD glacial-periglacial deposits on the Viso Massif, summarized by Mahaney et al. (2016a, 2022), is based on the position of the Durance/Guil terminal LG ice near Sisteron, France (44° 20'N, 5° 93'E, 448 m asl). The ages of these deposits are based on correlation with cosmic ray exposure (CRE) dates in the nearby Clarée Basin (Cossart et al., 2010), placing the full extent of ice at ~15.5 ka, with subsequent ~200-km withdrawal to the Mt. Viso plateau by ~13 ka. This places the ice cover that deposited ground and stillstand end moraine in the high-plateau area (Fig. 1) of the upper Guil valley during Allerød time (14–13 ka), with retreat punctuated by doublet stillstands at 2400–2500 m asl sometime during the mid-to-late LG event. In

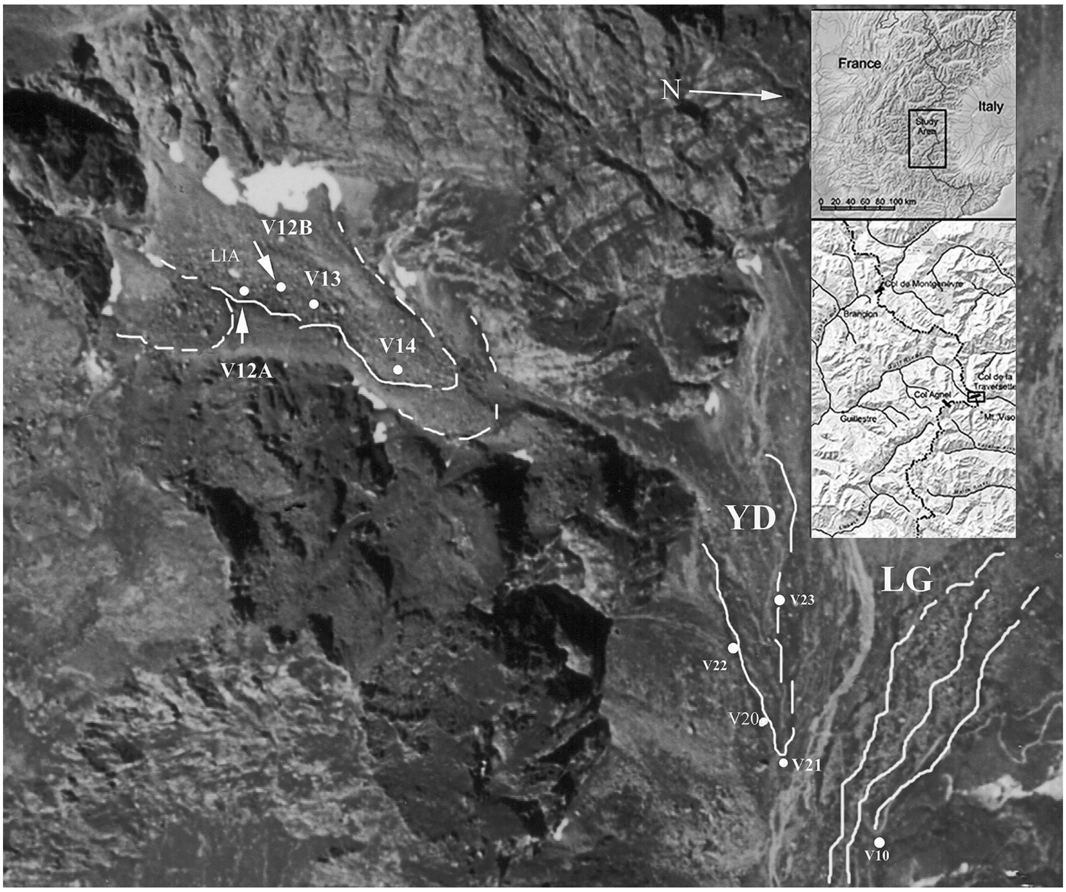

Fig. 2. Sites in the upper Po valley of Italy. The LG-YD relationship here is similar to other areas in the US Rocky Mountains where revitalization of the YD brought firn limits to nearly the elevation of the LG (Allerød) almost equalizing mass balances, catchment-to-catchment. On the Viso Massif these elevation differences are less than ~100 m.

unison with the French side, the subsequent withdrawal of the Po Glacier from its terminal position in the upper Po River canyon at ~680 m asl, near the town of Chisola (44°41'N; 7°15'E), to approximately 2000 m asl, kept pace with the Guil glacier retreat, over a similar time frame. Stillstand deposits in the upper Po catchment are less evident compared with the Guil valley, but of the multiple moraine ridges lacing the valley floor, two are prominent, as shown in Fig. 2. Despite the mixed lithologies between the two valleys, at present, the paleosols offer up near uniform depth (Fig. 3) with only minor changes in slope and with all sites exposed on high and well-drained topographies. A uniform section depth (45 ±8 cm) argues for time linearity since time zero, overcoming all other independent/semi-dependent variable influences.

The surface landscape, with its doublet stillstand moraines in the upper Guil catchment, is devoid of similar moraine records upslope of 2500 m asl. I speculate that the remnant LG ice was heated to inordinately high temperatures and almost instantly vaporized, leaving a clean bedrock floor up to the continental divide. All glaciers on the flanks of Mt. Viso appear to have been similarly subject to nearly instant removal, leaving in their wake only the LG ground/recessional moraines in their various forms with seral-state vegetation, initial soil profiles with variable A/C/Cu; Ah/Cox/Cu; Ah/C/R horizonation, all with coarse granular characteristics, sand-silt textures, and with pebble clasts embedded within at the surface. Thus, the conflagration left a carbonized surface, with all developing vegetation incinerated and most surface rock and surficial landforms possibly affected by high air pressures (P) to ~300 kilobars and temperatures (T) >2000°C. While we do not know exactly what pressure and temperature a cosmic airburst might produce, with dust loading the upper atmosphere, it was no doubt sufficient to produce a nuclear winter with an intense pulse or wave of heat, light, air pressure, and radiation. Relation of the hypothesized local airburst postulated here to production of cosmic dust retained per site is difficult to make without further work. However, the highest soot content recorded is in the vicinity of site V10 (Fig. 2) in the upper Po area generally in the area of highest Pt element concentrations. In relation to Tunguska (Svetsov, 1996), and more recently Chelyabinsk (in 2013) events, tonnage of cosmic dust produced over the Viso Massif, was probably much lower. Arguments over the vehicle that exploded over Tunguska have raged from meteor (Peplow, 2013) to comet (Gladysheva, 2020), with one reference to soil testing (Badyukov et al., 2011) that itemized magnetic spherules, Ni-Cr bearing magnetite and wüstite, glassy spherules and metal droplets, similar to what was discovered at Viso and in the Andes (Mahaney et al., 2013b). Unfortunately, the Tunguska research did not include reference to individual soil-forming factors, which might have further supported the near surface explosion of a vehicle yielding 5–10 megaton energy. Fesenkov (1961) made mention of cosmic materials recovered from terraces above the Chunya River, which included micrometeorites, Fe spherules, glassy cryptocrystalline spherules, and melted micrometeorites, but with no mention of soil morphogenesis factors equivalent to Jenny's Equation.

The proposed breakup of Comet Encke (Napier, 2010), its trail encountering several terrestrial sites, including southern Manitoba, where either an impact or airburst melted part of the Laurentide Ice Sheet, also is hypothesized to have detonated a fragment over Allerød (~13 ka) surfaces on the Viso Massif. The proposed airburst appears to have had enormous effects, melting much of the snow and ice surface it encountered, whereas elsewhere, similar airbursts affected land on several continents (Powell, 2022). This includes widespread melting; vaporization effects producing spherules upon cooling; fusing of mineral grains, sometimes in necklace forms; sands heated to melting temperatures with air-quenched features; and silt-to-sand-sized grains fused on heating to form buckyball-like objects. The rinds that existed at the time of the airburst suffered mineral distortion and packing, such that phalanx-like structures persist in surface pebble-sized clasts to depths of tenths of a micron, with surface structures weakened to allow diffusion of water penetrating deeper into the rock fabric such that both complimentary packages--P/T + oxihydration--can be identified Mahaney et al. (2012).

While carbonized bedrock is rare, airburst-affected sands and silts are common across LG deposits with reworked grains randomly spaced in YD paleosols. With surfaces undergoing erosional loss at ~12.8 kyr, most bedrock and rinds embedded in deposits are sometimes lacking cosmic evidence. This is not unexpected since rinds and bedrock surfaces are subject to grain loss, with such losses acting as material input to soils or to airstream grain pickup and removal. The area involved in this event is estimated at ~10 km^2 and the P/T vectors are thought to be differential, that is, not the same in every direction.

Aside from the physical side of the postulated airburst, the chemical side reveals a mix of in situ elements (ions) + influxed materials. Carbon, one of the common elements found either fused to minerals or as opaque masses, is sometimes mixed with oxihydroxide compounds or forms round to oval-shaped masses within weathering rinds. The carbon may have an origin from seral state vegetation, from vegetation outside the airburst area insourced by vacuum, or from the cometary vehicle itself. Elements with cosmic affinities, such as Co, Cu, and Cr, often have concentrations above crustal limits, along with a variety of platinum-group elements (PGE's) and rare-earth elements (REEs), such as La, Ce, Eu, and Lu. Aside from such anomalies, sediment bulk matrix materials in existing paleosols with elevated levels of PGEs (especially Ir and Pt) often with concentrations several orders of magnitude greater than crustal average, providing evidence that the conflagration was cosmic, not terrestrial in origin. Aside from proof of a cosmic chemical addition to clast rinds and paleosol profiles, such additives would also have been important to microbial components in the early evolutionary stages of soil development.

Recent research with six paleosol profiles (18 samples) in the upper Guil Valley of France brought forward standard DNA, with one exception in the Ah horizon of the G3 profile (Mahaney et al., 2012; Site G3, Fig.1 this paper), an aberrant bacterial strain that may be related to the YD-aged airburst. This study was carried out using DGGE analysis (Mahaney et al., 2013a) which may be related to the uptake of REEs by bacteria (Young et al., 2019) that requires various electron acceptors. A more in-depth approach focusing on functional genes is underway analyzing a greater number of samples and offering additional prospects.

Because some subsamples taken from paleosols appear unaffected by the cosmic event, I hypothesize much of the surface might have been snow-covered. If so, the high temperatures related to the bolide vaporized any exposed snow, ice, or standing water. Alternatively, some materials may have been affected but do not show intensive carbonization, and hence, escaped detailed analysis. Thus, only sands selectively affected by the airburst were recovered for analysis. P/T forces on bedrock shattered some rock adding material to soils, and these carbonized bedrock surfaces were later affected by erosion losses.

Here, we are dealing with partially molten material from the airburst, and these materials could contain contamination from the impactor itself. Thus, we have a molten fingerprint from the comet fragment that ties the produced spherules and melted/welded material with the airburst. Again, because some materials appear unaltered, this might be related to what happens when hot materials, such as glassy spherules become grounded, adsorb water, and over time, turn to clay. Other spherules may have become bound to larger particles before encountering water. Thus, fragments from airbursts are widely different in composition; some elements, such as Ni, Fe, Cr, and Cu, are enriched above crustal averages to high concentrations that are not common on Earth. The evidence thus far from this analysis is that parts of mineral grains and possibly some grains might have come from the fragment airburst itself.

3.2. The soils/paleosols

With the time frame established in the Mt. Viso area, from youngest (Late Holocene) to oldest (Late Pleistocene) (Mahaney et al., 2016a), the topography varies from cirque/valley bottom and slope positions to plateau surfaces mantled with Allerød to YD-age end/lateral moraine (Mahaney et al., 2022). The soil profile expression for Neoglacial-age deposits in the upper Guil valley ranges from C/Cu to A/C/Cu profiles (~10–25 cm depth; organic carbon <1 %; N in the hundredths %), that is, there are thin weathering horizons defying classification in the soil taxonomy (NSSC, 1995) ranging to thin Entisols. Older mid-Neoglacial age (~3 ka) profiles reach Ah/Cox/Cu horizonation (site G7, Mahaney et al., 2016a), still within the Entisol order. Their thickness ranges to ~30 cm with organic carbon concentrations at ~5 wt % and nitrogen at ~0.32%, which are about normal for younger mid-to Late Holocene deposits sampled in the upper Guil catchment (Mahaney et al., 2016a). In the upper Po catchment, alluvial fans exemplify simplified stacked Ah/C/Cu/Ahb/Coxb/Ahb/Cb/Cub profiles, forming immature pedostratigraphies that merge with deformed beds of oxidized and unoxidized sediment attributed to the passage of the Hannibalic Army (218 BC) (Mahaney et al., 2017a, 2018b). These all carry ^{14}C ages of reworked sediment in the disrupted beds, with greater ages ranging from ~4218 ±63 cal BP to 9840 ±35 yr BP (Mahaney et al., 2018b).

Above the ~2200-yr-BP beds, the younger pedostratigraphy described includes several aborted attempts at soil generation, each only averted by

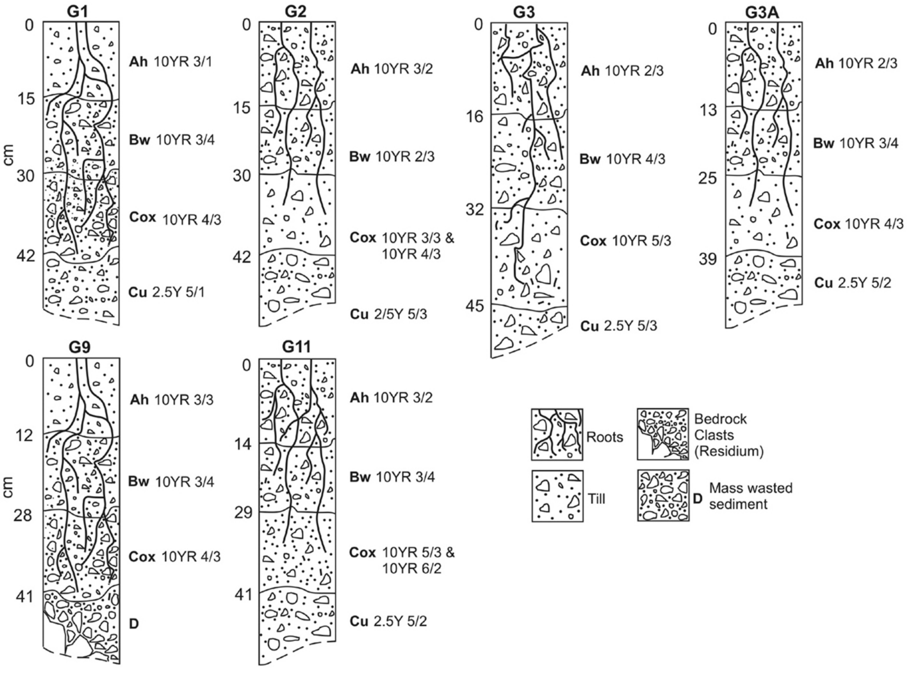

Fig. 3. Representative paleosol profiles in the upper Po valley. Distributions of cosmic-affected sediment is variable through all sections. G1 and G2 = Younger Dryas; G3-G11= Allerød). Section depths range from 32 to 42 cm. Average depth ~40 cm and amazingly there is little variance across all sections examined. Also, the color spread from the Ah to unweathered horizons (Cu) is fairly curvilinear – Ah (brown-grey) – Bw (stronger brown) – Cox (mottled brown-grey) – Cu (gray-yellow). (Mahaney et al., 2017b).

the deposition of younger sediment with renewed fan activity, rather common scenarios in mountainous terrain (Mahaney, 1990). These young Neoglacial-age soils are seen to represent what soils looked like on Allerød surfaces at or around the 12.8 ka YDB, at the time of the proposed airburst and accompanying conflagration. The soils would have had a granulometry of sand-silt mix with minimal clay components, certainly lacking in notable mineral weathering. Organic components, especially organic carbon/nitrogen at minimal levels on a par with what exists today in young soils of the upper cirques, in sites shown in Figs 1 and 2.

Soil evolution ranges from thin, immature Regosols/Entisols to more mature Inceptisols with Ah/Bw/Cox/Cu/D or R profiles reaching similar depths, and as shown in Fig. 3, nearly idealized colors are in the 10YR 3 and 4 range. Similar weathering depths in profiles with mixed mineralogies indicate that combined Late Glacial/Younger Dryas/Holocene climates combined in topographically similar aged sites to control weathering similarly, lithology differences aside in these valley profiles. The near horizontal horizon contacts, profile-to-profile, are somewhat unusual in alpine soils/paleosols and may come from the insulation effect of a thick snow cover inhibiting freeze-thaw.

3.3. Rinds

Average weathering rinds range from near-zero thickness in young Late Neoglacial age moraines to ~3mm for LG moraines, irrespective of mixed lithology as described by Mahaney et al. (2016a). Rinds, measured mainly in clasts with sizes ranging from ~2–3 mm, are considered near-permanent fixtures on deposit surfaces, resident since deposition during the LG and not subject to movement downward in underlying deposits. Nevertheless, rinds (ex. Fig. 4) are weathering sentinels (Mahaney et al., 2013a), recording incoming spores, allochthonous minerals, and even cosmic materials either from impacts or airbursts and precipitation with the latter producing invasive fluids moving inward and extending weathering deeper into the core-stone. With the Viso samples some clasts apparently escaped alteration by high P/T, but approximately 3/5th of clasts studied carry phalanx-like structures, with surface minerals rearranged into melted/welded masses in which the structures penetrate deeply ~700–800 µm. Subsequent weathering with water penetrating around dislodged mineral species over 12.8 kyr weathering time has produced an enhanced oxidized zone inward to the core-stone boundary.

If rinds offer any prospect of microbial life that might have survived the airburst and still carry

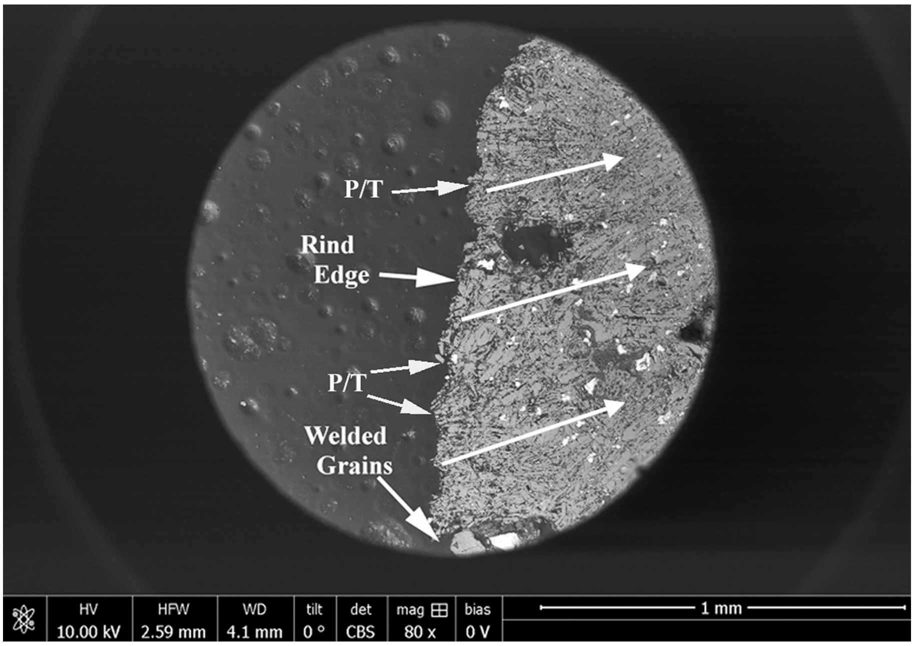

Fig. 4. SEM micrography of the G3 rind with a fragmental edge, vacuum cavities, white areas are Fe minerals, single species or assemblages. Close examination shows spiral areas (grain bulges) right of center that may be a product of P/T vectors as indicated; arrows project rearranged mineral phalanxes. Imagery from Dave Krinsley (University of Oregon). Annotation by WCM based on the original publication in Mahaney (2019). Enlarging the image with imagination brings other masses – dislodged circular forms that seem attuned to P/T forces nearly the full length of the image (Mahaney, 2019).

any aberrant DNA signature, it will likely be due to position on the clast surface, where bacteria are shielded in microfractures and cracks. Unlike paleosols where it is impossible to predict where grains from the original soil sediment are located in the studied profiles of today, it is possible to predict that most organic carbon present at the time of the airburst was volatilized and mostly lost to the weathering system. Any surviving mineral grains or opaque carbon were most likely distributed across the surface or forced downward in profiles. Surviving rinds weakened by high P/T conditions would likely lose material to the soil profiles (predicted by Dorn et al., 2017), prior to case hardening of the rind crust. The profiles thus affected extended downward over the next 12.8 kyr of weathering to develop average depths of ~40–50 cm with Ah/Bw/Cox/Cu horizonation. Over post-Encke time the organic carbon complex likely recovered to ~5 % within an estimated 1 kyr, based on current estimates of Neoglacial-age profiles below the Col de la Traversette (Mahaney et al., 2016a). The cosmic evidence tends to cluster in random, unexpected places, even in Cu horizons, given many throughput pathways or simple residence in situ from the airburst event. Not unexpectedly, some airburst evidence was presumably reworked given placement in various horizons of YD paleosols, even cropping up in Cu horizons presenting evidence of entrainment by YD ice post the 12.8 ka event.

The analytical description of rind weathering in micro-space adds another dimension to the paleoenvironmental history of rinds (Mahaney, 2019). This is especially the case with SEM analysis of the G3 rind (Fig. 4) showing the outer highly oxidized mineral masses (0 to ~700 µm) that are fully fractured and punctuated with opaque carbon, along with consolidated mineral phalanxes (arrows on Fig. 4) that were forced inward from the outer rind area (Mahaney et al., 2016b). These dislodged mineral masses form an irregular barrier or contact leading inward to a zone of oxyhydroxides that are stronger at the dislodged mass contact, becoming less strong inward toward the corestone with its inner contact rather sharp and distinct. This descriptive analysis is punctuated in places with EDS chemistry showing mainly C and Fe variations, all of which give the impression of P/T forces closing spaces between minerals packed in obscure forms. This process opens new microfractures that afford easy throughput of fluids to the rind interior, during which the oxidation front slowly extends inward as it disintegrates the clast body.

Rates of rind weathering vary across the globe and over time (Mahaney, 2019) with full rock consummation rarely achieved and dependent upon lithology and climate. In the case of the Viso Massif, time itself is insufficient to achieve full rock consummation, even considering the variable resident rocks ranging from gabbro/basalt to serpentinized peridotite, dolomite, and various forms of ophiolite. Even considering slow weathering environments in Antarctica (Mahaney & Schwarz, 2016), and Mars (Mahaney et al., 2012), the near-complete consummation of rinds is possible but may require millions of years. The slow disintegration of silicates leads to grus, a term normally ascribed to weathered granite, but with grain diameters for any lithology hovering between coarse sand and fine pebble grade sizes, diminishment of size increases as weathering progresses. From available evidence and given the humid climate, a case could be made that introduction of the cosmic factor to the soil-forming equation has led to increased soil weathering of macro and microelements. In addition, the increased body of certain REEs is of importance to the growth and development of the microbial ecosystem, especially certain 'normal' and aberrant species of bacteria that rely on electron acceptors (Young et al., 2019). More than this, given the presence of Fe-rich rocks, the release of Fe^{+3} assists in bacterial respiration, which in this case, may assist both normal and aberrant forms of bacteria.

3.4. Is 's' solvable?

First, it is important to view soil as an 'environmental reactor', an open system with myriad subsystems, all trying to achieve some form of equilibrium – physical and chemical – with most being far from equilibrium. Early on, in soil morphogenesis, mineral and chemical subsystems transmute through a series of system states that are subject to climate, acting with temperature and moisture to control weathering rates. These rates are often upset by climate variations, such that warmer and wetter conditions tend to speed weathering reactions, no matter the lithology in place. Early on, Jenny (1941) described soil as a physical system characterized by properties, for example: s_1, $s_{2,}$ $s_{3,}$ $s_{4,}$ where, for example, $s_{1=}$ N, $s_{2=}$ organic matter, $s_{3=}$ C, $s_{4\,=}$ pH. On this basis, a soil (weathering) system may have an infinite range of complexity. Functional interrelationships of properties such as these bear certain relationships to one another, such as $_{S1+S2}$ to $_{S4}$. Hence, again to paraphrase Jenny, 'F' (functional relationships: $_{(}s_1$, $s_{2,}$ $s_{3,}$ $s_{4\ldots\,=\,0)}$ identifies a system state, in this instance, time zero or the start-up-state. If one or more soil properties change, the system changes, and the soil assumes a new state: $\Delta N = \Delta s_1 = \Delta$ soil system. Integrating two properties yields: $\Delta N = \Delta pH = \Delta$ (new) system state. This is a theoretical state, so that the smallest change in any one property can give rise to a new soil. Such micro-changes in soil states, are intended to illustrate slight reverberations in the soil 'reactor' and would not be seen in the field. They are stated to provide a step up to a greater relationship between soil and environmental factors.

Second, additional soil properties may include moisture (cl′), biota (o′), and relief (r′), so $F\ (cl', o', r', s_1, s_2, s_{3, \ldots) = 0}$ describing a new system of greater complexity where environmental factors and soil properties are included. Weathering involves processes that transform parent material into soil, and these processes introduce time as the medium under which soil formation progresses. If climate is more or less unchanging, time is linear and soil formation is expected to progress linearly; if not, changes in climate may force rates of weathering to increase (higher moisture and heat) or decrease (lower moisture and heat), as long as all other properties remain uniform. With this intervention, the state (Δ soil) of the weathering system will change with time, forcing 3-dimensional space consumed by the system to undergo a volume change. The soil becomes a dynamic system governed by changes in soil-forming factors. For some: cl and o = active factors; r, p, and t = passive, but t is certainly a factor that changes, so it cannot be passive. Even r and p will change with time undergoing erosion and input of allochthonous materials, as demonstrated by Mahaney & Hancock (2022) who modeled the 0.8 Ma Teleki Catena on Mt. Kenya. Further, the equation of soil formation: S (s) = f (cl, o, r, p, t, **c**…) = o, with each factor considered independent or semi-dependent, it is hard to see just how factors can be labeled active or passive (Birkeland, 1999). Whereas solving 's' is elusive, part of the soil formation puzzle can only be realized by working up partial derivatives to assess each independent variable, one partial derivative at a time. Presumably, these derivatives stand independently and cannot add up to a sum ('s'), but they can shed considerable light on each factor in Jenny's equation.

While many have argued against the solvability of 's' in Jenny's equation (Jenny, 1941), the Russians most vigorously, Jenny carried on with varied attempts to expand on the soil-forming equation (Jenny, 1958, 1980), alongside modified versions by Johnson & Watson-Stegner (1990, and an in-depth approach across the Quaternary spectrum by Birkeland (1999). The equation's popularity amongst researchers placed the equation on a sound footing, as is evident with the 'factors symposium' (Amundsen et al,. 1994; held on the 50th anniversary of Jenny's book and with the publication of papers given by Amundson et al. (1994). Following this, the 3rd edition of 'Soils and Geomorphology', revised (1999) by Peter Birkeland, finally wove soils deeply into geomorphic and surficial geological research.

Simplifying soil, perhaps the most enigmatic of environmental systems, Jenny overcame criticism by finally using the equation to solve for individual factors, one at a time. To achieve this, one factor is established to vary, where all other factors are constant, or nearly so. Thus, as explained above in the introduction, solving one function at a time whilst all others are constant allows partial derivatives to be achieved, one function at a time. Hence, to discuss ($\blacktriangle s = \blacktriangle t$)cl,o,r,p,**c** (dt), the time factor, is considered a partial derivative of the ratio (ds/dt), and hence, one is forced to select sites where the time factor is variable. Many glacial sequences produce system states from zero (the present) through the Neoglacial, YD – LG, to the Last Glacial Maximum (LGM), and beyond, with some system properties coming into steady state (input = output) rather rapidly, others taking longer still. For example, organic carbon and nitrogen concentrations are known to achieve steady states from centuries to $\sim 10^3$ years, whereas particle size, clay mineral transformations, or release of Fe and Al oxihydroxides may not achieve equilibrium status (Mahaney et al., 2016a). It is these latter properties, when subjected to climatic change, as beyond the Holocene/Pleistocene boundary, for example, that require a system state reset with wet to dry climate rollover in many instances.

There are other often researched partial derivatives, such as: $(\blacktriangle s = \blacktriangle r)_{cl,o,p,t,\mathbf{c}}$ (dr) where the relief factor is considered variable, and where p, t, and **c** may be kept constant, but cl and o may show some variability. Some catenas (Mahaney & Sanmugadas, 1983) were generated over slopes of a few meters and that process may complicate cl and o on a micro scale with minor variations of moisture and vegetation from high to low catena members. One catena on Mt. Kenya (Mahaney & Boyer, 1986) in Liki III moraines (equivalent to Pinedale in the Rocky Mountains or Weichselian/Würm in Europe, i.e. 10–12 ka) set a standard for not only looking at the physical-mineral-chemical response to slope but with 'o', that is, with the microbial community varying, as well. Over larger spatial dimensions of ~50 m on Mt. Kenya (Mahaney & Hancock, 2022), profiles/sections range from high to low members in a catena, and they cross plant taxa lines from bamboo and Podocarpus to grass. This wide variation occurring within a pedostratigraphic complex further complicates the assessment of archived buried catenas in stacked paleosols. Assessing changes in the mineralogies and chemistries of each soil or paleosol in a catena is onerous enough, but attending to macroscale vegetation and microbial communities calls for multi-disciplinary efforts to establish changes due to slope variations. Such complications may be found in chronosequences, where changes in time may be complicated by changes in climate and where time may be a reductionist quantity if a sequence crosses the Holocene/Pleistocene boundary.

Focusing on parent material, perhaps the least partial derivative studied over the last decades is: $\blacktriangle p_{cl,o,r,t,\mathbf{c}}$ where (dp) is the partial derivative. In the Viso area where mixed acidic to alkaline bedrock is present, it is possible to pick soils developed only on selected bedrock, to study a lithosequence, but it is quite impossible to use glacial deposits with a mixed lithology. A climosequence may be established with $\blacktriangle cl_{o,r,p,t,\mathbf{c}}$ with (dcl) the partial derivative, partly complicated by function 'o' following changes in 'cl'.

Thus, to sum up, partial derivatives for each factor provide the only logical means to solve for 's', the enigmatic environmental system interface between the atmosphere, lithosphere, biosphere, hydrosphere, and cosmosphere, perhaps representing the most complex matter-energy system on planet earth. The soil is enough of a network of physical-chemical-mechanical-biotic subsystems by itself, made more complicated by cosmic intrusions from time to time. YDB evidence on Mt Viso is only one example of 'c' intruding the soil equation; other examples cropping up include the Hopewell event (Tankersley et al., 2021) of the mid-Holocene covering a large extent of the lower Ohio Valley in the U.S.; the YDB event over part of the Dry Valleys in the Antarctic (Mahaney et al., 2018a); the airburst over the Mucuñuque Valley in the northwestern Andes (Mahaney et al., 2013b); and destruction of the Tall el-Hammam city a middle Bronze-Age place in the Jordan Valley (Bunch, 2022). Chemistries above crustal averages on Mt. Kenya in paleosols of LG age may also signal a cosmic event, if work underway with analysis of sand separates produces positive results.

Aside from new cosmic sites coming on stream (Moore et al., 2020; Mahaney et al., 2022; Tankersley, 2022; Bunch, 2022, few will involve soil analysis as was done here in the Viso Massif and the Northwestern Venezuelan Andes (Mahaney et al., 2013b). The Viso data recorded here involved both paleosols in glacial sediments and clastic rinds in deposit surfaces related to younger superposed YD moraines, the latter with reworked cosmic-affected sediment. Here the LG/YD-deposit chrono-relationships are based on superposition or surface spatial relationships, whereas in the Andes, the YDB layer is buried within a glaciolacustrine/glaciofluvial succession with the ~3-cm thick YDB layer being similar in every respect to other YDB layers referenced worldwide. Presumably, in future, new sites, paleosols on the surface or in pedostratigraphic successions will present opportunities to test the Viso findings. It will be particularly important to search for elevated concentrations of base metals, REEs, and PGEs (especially Pt and Ir) with respect to electron acceptors and DNA composition that might relate to the microbial ecology following a cosmic event. This is especially the case where sites are related to LG-YD moraines that can be dated by C14.

4. Conclusions

Soil morphogenesis studies followed a long, discomfiting path since inception in 1883, including several decades of attempting to tighten and integrate the main factors of soil evolution, and in the process, highlighting some and downplaying others. The early focus on relief ('r') and time ('t') paved the way for an early influx of papers, with an uneasy attempt to hold one factor variable with others constant. Even relief ('r') attained enough status that a journal, *Catena*, came on board to bring toposequences to the forefront, proving that in some instances ($\blacktriangle s/\blacktriangle r$) with $_{cl,o,p,t,\mathbf{c}}$ = (dr) held constant, the topographic factor 'r' is considered a partial derivative of the ratio (ds/dr). Hence, one is forced to select sites where topography is variable from the upper member, across the backslope and footslope members to the toeslope. Such studies only become confounded when the catena involves buried pedostratigraphic members, such as on Mt. Kenya (Mahaney & Hancock, 2022), where archival catena members outline pre-LGM weathering.

Taking the soil-paleosol-forming factors of Jenny (1941) and Birkeland (1999) into account, soil/paleosol genesis is seen to rely firmly upon the functional interrelationship of each factor. Thus, while 's' is illusive, cl, o, r, p, t, and $\mathbf{c}$, may be studied as partial derivatives of the equation with each factor considered independent or sometimes semi-dependent. Taking all partial derivatives of the equation into account, this is about as far as it is possible to solve for 's'. And as new cosmic sites are uncovered from time to time, soil morphogenesis is likely to come forward as an important tool to couple the five normal independent variables with the new cosmic (**c**) variable. What is paramount here is that Jenny's pioneering efforts, supported by Birkeland (1999) and followed by many workers the world over, show that soil genesis in many locales provides models for the study of soil to paleosol morphogenesis. As indicated here, the cosmic relationship on the Viso Massif unfolded intuitively from an unrelated project – classics-geoarchaeology to glacial-soil stratigraphy and on to cosmic history. Workers studying the LG/YD transition in various areas would be advised to look for cosmic evidence (elevated base metals, REEs, PGEs, Pt/Pd ratios) in Allerød/YD paleosols, the former for primary evidence, the latter for reworked sediment.

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