Soil morphologic indicators of environmental hazards linked to cosmic airburst

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Abstract
Distinctive soil morphologies and fingerprints of cosmic airbursts are identified by comparing speculated impact-linked situations from various past records with three well known airburst events: the 1908 Tunguska event (Central Siberia), the Darwin glass layer (Western Tasmania) and the Henbury crater field (Central Australia). The signal of cosmic airbursts is isolated from the local background by high resolution observational and multi-analytical data. Two groups of anomalous debris are recognised: (G1) exogenic, metal rich organo-mineral components derived from terrestrial precursors, possibly tracing the collider; (G2) carbonaceous polymorphs formed by thermal cracking of G1volatile components that pulverised on the local vegetation. The association of G1 and G2 debris with a patchy pattern of fluffy ash and baked soil aggregates are characteristic of local ignition induced by the pyrogenic compounds of the heated collider while entering the atmosphere. Impact glass layers formed by pulverisation at the surface of the exogenic hot debris jet, but not from melting of the local soils. High resolution soil studies should contribute to further elucidate natural hazards linked to cosmic airburst, particularly firing effects due to local ignition by pyrogenic debris, acidifying risks from pulses of carbonaceous aerosols and long lasting contamination by resistant metals.

Key Words
Debris jet, pulverisation, ignition, carbonaceous polymorphs, metals, terrestrial

Introduction
For long questioned as a reality of the Earth history, impact hazards generated by low-altitude airbursts from hypervelocity asteroid impacts are now speculated to occur frequently with damage on ecosystems and human populations (Osinski *et al.,* 2008). However, the cataclysmic landscape with 4000 km^2 of devastated forest left by the 1908 Tunguska explosion in central Siberia remains so far the only observational data for calibrating processes linked to cosmic airbursts (Boslough and Crawford, 2008). The low range surface effects resulting from the blast waves and thermal radiation of the high-temperature jet of expanding gas would be more severe than for nuclear explosion of same yield. Larger cosmic airburst would generate a hot jet of vaporized projectile able to form the typical flow-textured impact glass by high temperature melting of the surface. In addition, airburst phenomena could produce small craters with impact melt fragments due to the impactor disruption at some significant altitude (Newsome and Boslough, 2008).
Here, the observational data of selected situations contribute to further explore the suite of processes generated at the soil surface by cosmic airbursts. We identify distinctive soil facies with their diagnostic tracers that are important to evaluate the range of environmental hazards linked to this specific phenomenon.

Materials and methods
Thirty bulk and undisturbed samples are studied from three situations that are representative of the main types of cosmic airburst for defining the specific morphology of the impact-linked soil facies and their associated markers in each case. The 1908 Tunguska layer identified by high resolution sampling on two peat sequences provides observational data to evaluate effects at the ground of the high-temperature fireball, assuming from previous studies total ablation of the collider (Svetsov, 1996). The scenario of surface melting is represented by the 400 km^2 strewnfield of Darwin glass in Western Tasmania with its distinctive layer just below the modern humic horizon of glass debris that were dated by Ar/Ar at ca. 0.8 Ma (Howard, 2008). The Henbury crater field in Central Australia provides data to study effects of airburst-linked cratering on the surrounding soils (Ding and Veblen 2004).
We compare these reference sites of airburst events with anomalous soil morphologies that we speculated to be of impact origin due to the association of a patchy highly fired surface with exogenic debris formed of vesicular glass, partly melted and unmelted clasts (Courty *et al.,* 2008). The studied sites are located in the Middle-East, France and Peru. They comprise buried soils dated from the terminal Pleistocene, from ca. 4 kyr BP, and debris concentrations at the present soil surface. The spatial pattern and the microstratigraphic expression of the anomalous soil morphologies have been examined from widely exposed surfaces and serial trenches. Undisturbed samples for thin section preparation were preferentially collected from the finest microstratigraphic records and from intact concentrations of debris including refitting fragments. Individual

micro-strata and patchy domains showing distinctive properties (colour, structure, debris concentrations) were sampled and subsequently water-sieved through the following meshes: >2 mm, 2-1 mm, 1-500 µm, 500-200 µm, 200-100 µm. Systematic examination of the residues under the binocular microscope was performed to isolate the anomalous signal from the local background. After gentle crushing and water-sieving, inclusions were extracted from the coarse debris and from the impact glass and compared with those of the host soil matrix. The preparation procedure was carried out with great care for controlling contamination by industrial products, especially abrasive paste or paper, nylon films, polymer resins, diamond paste or spray, detergent and metals. Observations were conducted in a microanalytical environmental scanning electron microscope (ESEM-EDS) on uncoated specimen. The possible contamination of polished specimens (studied using SEM-EDS and SEM-WDS) by diamond polishing and conductive coating was controlled by comparing to a raw slice. In situ mineralogical identification of individual particles down to 1 µg was performed by transmission X-ray diffraction. Representative particles were selected for Raman micro-spectrometry, isotope analysis (C, Cr, Fe, O, S), IR-GC-MS analysis, ICP-AES analysis and total chemical analyses. Dating by AMS C^{14} radiometric dating was performed.

Results

We identify similar unusual components that contrast from the respective local soil materials which can be separated in two groups according to their association with distinctive fractions of the host matrix: (G1) an exogenic assemblage of discrete particles occurring both as disseminated grains in the host matrix and as inclusions in the coarse debris and the true impact glass; (G2) components which do not occur as inclusions in debris and glass, often associated with plant debris that are common in the host matrix.

G1 comprises various types of metal rich mineral and organic components that are often associated with marine microfossils, fragmented, melted or intact (Fig. 1a, 1b, 1c). Native metals (Fe, Fe-Cr, Fe-Cr-Ni, Cu-Zn, Cu-Zn-Ni, Pb, Pb-Cr, Al and Cr) are found as discrete spherules, ribbon-shape films and flakes and splashed droplets at the surface of the exogenic mineral grains. These components comprise various types of minerals, glass spherules and glassy flakes, fine-crystallized breccias and rock clasts of sedimentary and igneous origin. The organic components occur as discrete domains of amorphous carbon, often more graphitized, and commonly associated with hydrocarbons and aliphatic polymers. Pure carbonaceous grains are also encountered as translucent to blue blocky particles made of aliphatic polymers and grey, white or pale blue, crumby to ribbon-shape particles of polystyrene, and vesicular bitumen fragments. Soluble salts are encountered as either grains or neoformed crystals on the mineral grains, consisting of potassium and sodium chloride, barium, calcium and more rarely strontium sulphates. Individual spherules and spheroidal agglutinates of framboidal iron sulphide are common.

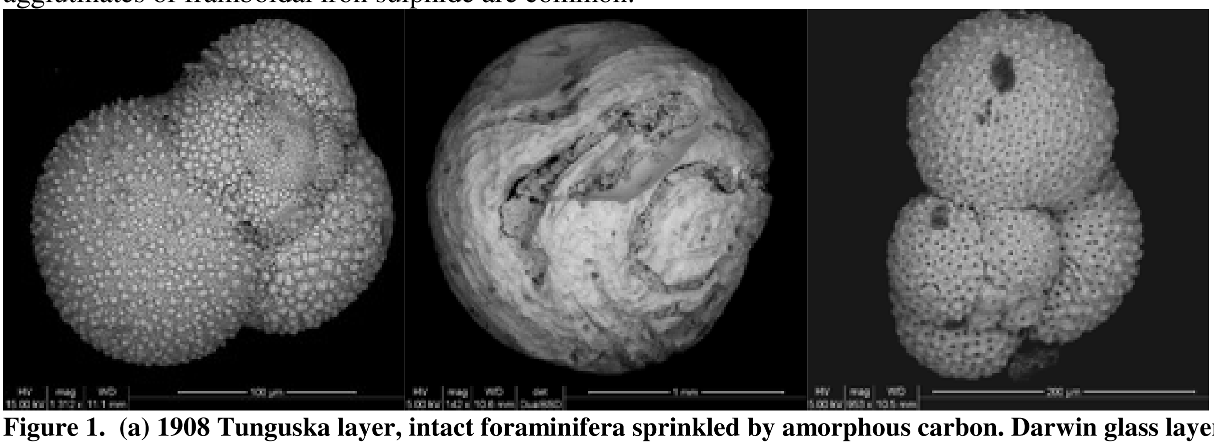

Figure 1. (a) 1908 Tunguska layer, intact foraminifera sprinkled by amorphous carbon. Darwin glass layer: (b) flow-textured glass spherule extracted from the fired soil surface: amorphous carbon and melted marine mud filling the cavities; (c) intact foraminifera sprinkled by amorphous carbon extracted from the Darwin impact glass.

We found commonly compound white carbonaceous fibres with nodules formed of fine quartz embedded within a green polymer glass sprinkled by native metals. Hexagonal crystals of sp^3 carbon have been identified by high resolution TEM in the green nodules and confirmed by XRD to be chaoite.

The G2 components consist of various carbonaceous polymorphs: translucent to coloured hollow fibres; hollow to vesicular carbonaceous spherules similar to those encountered in the ash residues produced from power plant stations; vesicular black vitreous grains; dull orange, brown, grey, green or pale blue, rubbery carbon grains. The plant debris occur as charred residues and translucent to slightly coloured intact fragments of stems and leaves. Charred residues with their distinctive plant morphology are often

agglutinated by vitreous or microspheroidal graphitic carbon. Silicate cement showing partly melted coccolithic mud, Ca-sulphate and sulphide, droplets of Ba-sulphate, zircons, euhedral crystals of rare earth phosphate, droplets of native metals of various composition (Ag, As, Au, Bi, Co, Hg, Ni, Pt, in addition to the ones listed above), are present at the surface and in the vesicles of the G2 components and on the plant debris. Lonsdaleite, i.e. detonation diamond, has been identified by Raman spectrometry in carbonaceous domains embedded in the silicate cement on the carbonaceous spherules.
Powdery white to brownish grey ash identified in the field as thin lenses or loose filling of subsurface root channels display high amount of carbonaceous fibres and spherules, finely mixed with calcinated plant fragments showing an internal carbonized part. The greater abundance of G1 components is observed in the ashy domains, occurring as individual particles ranging from sand to fine silt. In thin sections, the soil surface below the ash lenses often show an open packing of fragmented aggregates that locally have a baked-brick aspect. Ash lenses are also observed at the contact between the most intact concentrations of coarse vesicular debris or of the true impact glass and the underlying weakly baked soil surface. Careful control from these zones shows in the host soil matrix a size continuum from coarse sand to silt-sized debris of G1 components with angular shape.
Isotopic analyses performed on Fe, Pb, Cr, sulphur, oxygen and carbon are in agreement with a terrestrial origin of the precursor materials.
Radiocarbon ages of 2700 +/- 40 yr BP and 950 +/- 40 yr BP have been obtained respectively for vesicular carbon pine bark and pine wood extracted from the 1908 peat layer at Tunguska.
A radiocarbon age of 1820 +/- 40 yr BP has been obtained on charred wood extracted from the ashy burnt soil surface ***just underlying*** the layer of Darwin glass. Close to zero C^{14} activity has been obtained on the bitumen fragments and the vitreous graphitic carbon.

Discussion and perspectives

The observational and analytical data obtained on the three reference situations of cosmic airbursts help to elucidate the controversial aspects from earlier studies, and open an unexpected issue. In contrast with previous assumptions (Jehanno *et al.* 1989), the terrestrial origin of the exotic components occurring in the 1908 Tunguska peat layer is unlikely to derive from later fall of industrial contaminants. The compositional coherence of the well sealed layer supports a synchronous fall of airborne debris resulting from a collider including components of terrestrial origin. The intimate incorporation of fine G1components into the charred and calcinated plant fragment (G2) suggests that the local vegetation was pulverised by a hot debris jet containing metal particles and carbonaceous volatiles. High amount of kerogen precursors (i.e. G1 organic components) in the debris jet would explain its pyrogenic efficiency on the local vegetation and the formation of the G2 organic components by thermal cracking. The two old ^{14}C values on the local charred pine express contamination by the dead carbon from the graphitic compounds at the time of burning. The lonsdaleite and the sp^3 hexagonal carbon incorporated into the pyrogenic debris would trace transformation by detonation of the graphitic carbon at the exact time of flash heating.
The similar observational and analytical data for the Darwin glass layer suggest that the airburst processes relate also to the explosive pulverisation of a hot debris jet from space of terrestrial origin. The sharp contact of the glass layer with the underlying fired soil surface, its compositional contrast from the local rocks, and especially the marine microfossils, preclude their formation from surface melting. The recent C^{14} age of the associated burnt layer is coherent with its position just below the weakly humified surface horizon and the nearly intact assemblage of glass debris. The active suite of glacial periods and soil forming episodes for 800 000 years on the Tasmanian dissected landscapes would have severely degraded a glass layer formed so long ago at the surface. This questions the exact significance of the 0.8 Ma Ar/Ar age of the Darwin glass.
Unfortunately, the over-picking of meteorite fragments and impact glass around the Henbury crater field, plus the scarce soil cover, have left nearly nothing for understanding the link between crater formation and airburst processes. However, the remaining patches of vesicular glass formed of exotic G1 debris of terrestrial origin suggest that the collider forming the crater field might have included a terrestrial component together with the fragments of the medium octahedrite IIIA iron meteorite.
The analogies between the anomalous soil morphologies from the various sites studied with the 1908 Tunguska layer and the Darwin glass layer support the hypothesis of their formation by airburst processes. The surprising similarity of the G1 components of terrestrial origin for situations of different ages and various contexts remains intriguing. Further investigations will help to test the hypothesis of occasional collisions between cosmic projectiles and terrestrial debris that were formerly launched to space by lithospheric cryptoexplosion (Morgan *et al*. 2004) Showers of terrestrial debris might not have been previously identified simply because only extra-terrestrial colliders are assumed so far to have bombarded

the Earth. Because of their resemblance to kerogen-derived industrial products, the G2 components, might have been viewed as field or laboratory contamination, or plant fibres. Their embedment by polymer films seems to have protected weakly resistant G1 components, especially the soluble salts from leaching, and the native metals from oxidation. The surprising resemblance of the powdery ashes with industrial ones from power plant station simply expresses similar combustion processes by pulsed air of fossil combustible. However, the original formation of polymers would express high volatile content in the colliding debris jet. The patchy pattern of the ash lenses and fired domains shows that ignition by the pyrogenic compounds was erratic, depending upon production of volatiles in the hot debris jet.
These cosmic airbursts might also have ignited large scale wildfires in sensitive regions, just alike the disastrous ones initiated after drought of forested areas by lightning strikes or human incautiousness. Massive production of combusted biomass would probably dilute the original pyrogenic products, although the resistant vitreous carbon might be long lasting marker of the impact-linked ignition in contrast with the fragile charred fragments. The 1908 situation encountered in Central Siberia shows that there was not only surface devastation, but also thermal radiation from cosmic airburst which might have been lethal to many animal and human inhabitants, possibly inducing local mass killing of flocks. Finding for the distinctive fingerprints of the flash heating in the soil matrix embedding the bone accumulation would help to determine the exact cause of animal brutal death from past situations.
Future research will intend to trace effects in the soils that witnessed cosmic airbursts of the atmospheric perturbation caused by the carbonaceous aerosols, possibly acidification and precipitation increase due to cloud condensation nucleation processes. Detecting in past soils the long lasting contamination of the ecosystems by toxic metals that might have been critical for animal and human health is also a challenging issue.

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