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Weathering rinds: Unlikely host clasts for evidence of an impact-induced event

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ABSTRACT

Interhemispheric evidence of a cosmic impact 12.9 ka is known now from North to South America, Europe and Eurasia, all data supporting a cosmic event derived from cores and from geological sections. Most databases supporting the impact hypothesis at the Younger Dryas Boundary (YDB) rely on high-temperature microspherules, melted minerals, cracked clasts, presence of nanodiamond, high-temperature scoria, high Fe/Ni ratios, pdf's, shock melted quartz, high $^{10}Be/^{9}Be$ ratios and occasional presence of platinum metals. Controversy over the impact, the so-called Black Mat enigma, and its relation to the Younger Dryas readvance at the end of the last ice age, is fueled by arguments over whether a single extraterrestrial impact might sustain a 1 kyr-long downturn in insolation engendering a substantial increase in worldwide ice volume. New evidence in the form of impact microfeatures – extreme breccia, high crack propagation, thick carbon encrustations and partial to full shock-melted/contorted grains – in weathering rinds from the Western Alps, France, as documented here, adds to the growing body of evidence that the event was truly widespread, if not worldwide in effect. Whereas evidence of cosmic impacts may be erased by glacial and fluvial erosion in high alpine areas, such events as demonstrated herein are recorded as punctuated time-stratigraphic events in microcosm, preserved in weathered clasts.

1. Introduction

Climatic cooling and forcing of the Younger Dryas advance during the Late Glacial have a long and turbulent history with many workers documenting evidence for glacial resurgence of the Laurentide Ice Sheet (Teller et al., 2002), cooling in the North Atlantic (Lowe et al., 2008), whereas others focused on various high mountain locales (Birkeland et al., 1989; Reasoner et al., 1994; Hansen, 1995; Osborn et al., 1995; van der Hammen and Hooghiemstra, 1995; Rodbell and Seltzer, 2000; Mahaney et al., 2008). What caused climatic cooling when Earth's insolation curve during the Bølling-Allerød fueled glacial recession? As the evidence for a glacial advance multiplied, all of it came from glacigenic landforms and palynology with little satisfactory explanation as to what caused the climatic shift. While various researchers measured weathering rinds to obtain relative ages on Last Glacial Maximum (LGM) and post-LGM deposits, no one thought evidence that could answer the question of the YD climatic reversal might reside within weathering rinds. However, rinds have lately been shown to contain considerable paleoenvironmental evidence, and in some cases throughout much of the Quaternary (Mahaney et al., 2012a,b). Rinds in clasts on Mars (Mahaney et al., 2012) may provide, in addition to weathering and impact records, the much sought-after proof that life exists or has existed on the Red Planet. The Mars Science Laboratory (MSL-Curiosity) has on board drilling equipment designed to recover and analyze rind material in much more ancient rock.

Since the discovery of a thin (2–5 cm), black or very dark sediment layer, widely distributed over interhemispheric distances, considered by Firestone et al. (2007a,b) to have a cosmic origin, controversy over its relation to the Younger Dryas glacial advance has fueled a literature avalanche (Firestone et al., 2007a,b; Kennett et al., 2007, 2009; Haynes, 2008; Pinter and Ishman, 2008; van der Hammen and van Geel, 2008; Broecker et al., 2010; Mahaney et al., 2011b). The absence of a crater to link the impact event with a particular place on Earth led to the theory of an airburst (Napier, 2010), presumably a comet break-up over southern Canada, at approximately 12.9 ka (Bunch et al., 2012). Hence, the Younger Dryas Boundary (YDB) is identified as the starting point for the YD ice resurgence in the Late Glacial record. The airburst/impact event is linked with YD ice resurgence at a time when the insolation curve (Bølling-Allerød warming (Liu et al., 2009)) was forcing glacial recession worldwide, a trend reversed in many areas by ice readvance — the YD reversal.

Dated black mat beds vary in terms of their closeness to the 12.9 ka cosmic event, but most are within plus or minus two centuries and based on calibrated radiocarbon dates with very narrow standard deviations. What sets the black mat beds apart from normal glacigenic, fluvial, glaciolacustrine and aeolian sediment is the usual black (10YR 1/1) color (Oyama and Takehara, 1970), the normal hue of either bog sediment or dense and mature organic-rich material in paleosols. It is the examination of this material that yields totally unexpected glassy carbon spherules, planar deformation features

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(pdf's), partially melted grains, shock-melted quartz and other minerals, weighty magnetic fraction, particles and full mineral grains consistent with high energy collisions and extremely high temperature, sufficiently high to melt quartz (1500 °C). What seems to be most prevalent in high mountain sites at great distance from the supposed impact point is thick carbon, either coated grains or carbon interwoven in complex fashion with quartz and other minerals (Mahaney et al., 2008, 2011a).

Whereas black mat sediment has been found in glaciolacustrine and glaciofluvial deposits (Mahaney et al., 2008, 2010, 2011a,b) in the Andes, most occurrences are documented in low-lying areas in the American southwest and southeast, in Mexico and Syria (Bunch et al., 2012), coastal France, Peru and Central Asia (Ge et al., 2009) to name a few well documented localities. The YD event remains relatively undocumented in the French Alps, although considerable work on the YD glaciation has been done elsewhere in Switzerland and Italy (Ivy-Ochs et al., 2009).

2. Field area

The criteria for the YD impact are similar to that used to prove the K/T impact (Hildebrand, 1993) with the exception that the Alps evidence is in metamorphic terrane which was under glacier recession at the time of impact. The deposit investigated is located at 2450 m a.s.l. (Fig. 1) in the upper Guil Valley, France, and contains recessional moraine sediment of Late Glacial (LG) age. The location, measured by GPS, is 4952235N; 32345383E.

The evidence resident in weathering rinds in clasts on the inner LG recessional moraine is located in front of a doublet moraine of presumed YD age. While ^{14}C dates are not available for the LG and YD moraines, the outer YD moraine buries part of the inner LG recessional (Fig. 1), the result of a glacial readvance. The lack of lakes/bogs suitable for coring makes it almost impossible to find sites with resident impact beds still intact, and clasts on LG deposits are the only repositories of the cosmic impact discovered to date in the French Alps.

The Guil Glacier fed ice into the larger Durance Glacier during several Pleistocene glacial stages, the latter constructing a succession of end moraines of pre-Würm (Weichselian) and Würm age near Sisteron (450 m a.s.l.) in the lower Durance Valley. Ice recession at the end of the Würm Glaciation was rapid, the only prominent recessional moraines located at 2400–2450 m a.s.l., and the innermost group prominently overrun by a glacial readvance, presumed to be the YD. Because both paleosols within and weathering properties of coarse clastic debris (rinds) on the LG and YD deposits are similar, they must have an age separated by centuries or at most a millennium.

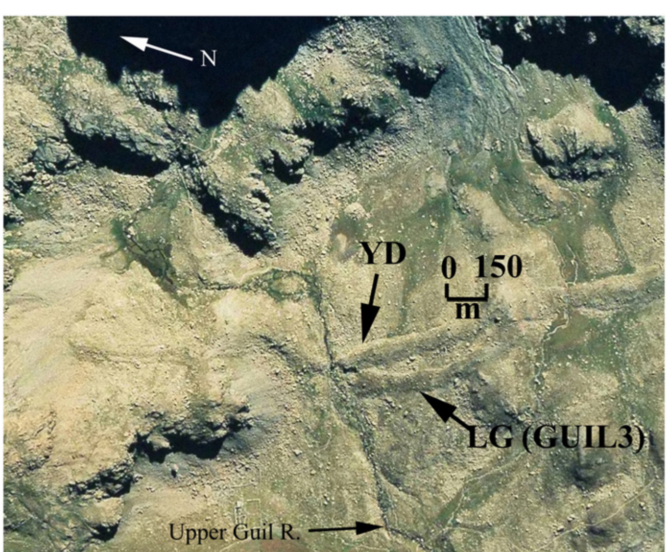

Fig. 1. Location of the Late Glacial (LG) and Younger Dryas (YD) moraines in the Upper Guil Valley, French Alps.

The Guil Catchment (Fig. 1), a near linear fault-controlled glacial basin with headwaters on the western slopes of Mt. Viso (3841 m a.s.l.), is the type locality where the first evidence of a cosmic impact was discovered during analysis of local weathering rinds in 2008. The lower valley which trends NW–SE is marked by numerous bedrock bars, each punctuated by 50–100 m drops in elevation down to an elevation of ~1900 m a.s.l., approximately the trailhead leading up to the Col de la Traversette where the valley widens out appreciably. Above 1900 m, the valley is floored with bedrock, talus cones and successive debris flows dominating the valley sides. Between 1900 and 2400 m elevations any recessional moraines put down by stillstands of receding ice would have been short lived given active erosion expressed on both the north- and south-facing valley slopes. Soils in these deposits are thin Entisols (Cryorthents mainly, National Soil Survey Center, NSSC, 1995) and lichen cover, while variable, generally does not reach 50 percent and maximum lichen diameters are in the 40–50 mm range, considerably lower than on stable moraine surfaces in the upper valley. It is from these source materials, sparse vegetation and associated thin Entisols (National Soil Survey Center, NSSC, 1995; Birkeland, 1999; alpine grassland soils) that some of the carbon in the impacted clasts might have accumulated when an impacting high-temperature cloud descended upon the area producing a conflagration that would have destroyed all life, including plants in what was probably a wet tundra in its early developing seral stage. Steep slopes are present just above the LG/YD moraine limits leading up into a prominent cirque below the Col de la Traversette (~3000 m a.s.l.; Mahaney, 2008), the bedrock floor of which lacks even ground moraine, much of the surface covered with Little Ice Age rockfall and talus. While it is impossible to determine whether or not the LG ice receded into the Traversette Cirque prior to the YD, it is certain that the YD ice advanced to 2450 m at a later date.

Situated west of the high summit of Mt. Viso it is certain that the mountain provided a significant barrier to the passage of westerly winds which even today produce tens of meters of snowfall in winter. A downturn in temperature, possibly caused by the YDB impact, followed emplacement of the LG moraine and led to the YD advance.

During the last glaciation, ice first retreated toward the Traversette Cirque and an unnamed cirque to the south nearly below the summit of Mt. Viso; the situation reversed with the advent of the YD cooling event. These glacial oscillations left a wealth of glacial geomorphic and sedimentological evidence including coarse clastic debris as host material, weathering rinds of which contain evidence of a cosmic impact, presumably the progenitor of the Younger Dryas (YD) climatic reversal, the latest event in the Late Glacial record (Ralska-Jasiewiczowa et al., 2001; Gibbard, 2004). This latest of Late Glacial events – the YD – is superimposed on a cooling trend which started 14.7 ka (Lowe et al., 2008), maximum cooling starting at 12.9 ka. The question of whether or not the cosmic impact could have generated the YD reversal is still debated in the literature. A recent review of the YD event by Broecker et al. (2010) puts the YD event into context against the Late Glacial cooling trend. These authors, unconvinced of a cosmic spike generating the accelerating cooling necessary to cause a glacial advance that lasted for 1 kyr, argue that climate reversals similar to the YD appear to be normal perturbations during previous glacial terminations; hence they are not the result of catastrophic events.

From a search of all glacial/fluvial outlets in the research area, streams draining across steep gradients (10–35° slopes) into the Guil River preclude finding terraces of LG age that might carry a record of a cosmic impact. Cores (unpublished) retrieved from a mire (Fig. 1) within the YD moraine belt revealed only a Middle Holocene record beginning ~4 ka (personal communication, R. Dirszowsky, 2012) and the lack of bogs or lakes as basins that might contain cosmic

Fig. 2. Macrophotograph of a representative GUIL3 weathering rind (arrow). The rind is variable with a mean thickness of 2.5 mm.

impact sediment, means that rinds in clasts on LG moraines probably contain the only record of a cosmic event. New investigations in other catchments might reveal geomorphologic and stratigraphic information, all of which might build on the database presented here, documenting a resurgence of ice following the break-up and retreat of glaciers in the Late Glacial. Ice overran older Late Glacial moraines consisting of till and glaciofluvial sediments which are only possible to date using relative age criteria.

3. Materials and methods

The black mat bed, normally a 2–3 cm-thick encrustation of C + Fe + Mn on pebbly sand of felsic gneiss and granitic composition, together with glassy carbon spherules, as found in the Andean Mountains (Mahaney et al., 2008), is missing in the Guil Valley of France. As shown in the Andean example, the burnt layer material represented by a high carbon signature was first thought to result from a lightning strike and resultant fire, although the conflagration temperature in a wet tundra undergoing first or second stage succession vegetation growth would not be high, certainly not high enough to produce glassy C-rich spherules firmly fixed to mineral surfaces. Admittedly, the C-spherules present elsewhere have not been observed within the rind samples in the Alps. However, the associated carbon welded onto pyroxene, olivine and quartz, dislocated and partially melted and shocked pyroxene species together with brecciated mineral grain surfaces, presumably resulting from impact, leads to a testable hypothesis more in line with previously reported data (Mahaney et al., 2011a,b). The high carbon layer in the rind material is similar to the burnt material correlated by Mahaney et al. (2010) with the black mat beds described elsewhere in North and South America, Europe and Central Asia.

Clasts were split with a rock hammer and measured to obtain mean rind thicknesses and standard deviations, to assess relative age differences of deposits. Rinds were measured to the nearest half mm and data were recorded. Rinds were cut with a slab saw, and photographed, and subsamples were studied under a Leica SAO 80 light microscope that were later milled to create sections that could be studied by SEM/EDS. Selected rind sections were then mounted on stubs for analysis by normal SEM (SE) and (BSE) and Energy-Dispersive Spectrometry (EDS) following methods outlined by Mahaney (2002). Because carbon is important in this analysis, samples were coated with gold–palladium (Vortisch et al., 1987; Mahaney, 2002). Photomicrographs were obtained at accelerating voltages of 20 keV. X-ray microanalysis was acquired at an accelerating voltage of 20 keV.

4. Results

Rinds in metabasalt clasts on the GUIL3 moraine (Fig. 1) yield a mean maximum thickness of 2.9 mm with a mean minimum thickness of 0.6 mm, and thickness of each clast measured to 0.5 mm. Rind growth, like most natural processes, is subject to differential effects with chemical and biological energies being applied differentially across a surface (Mahaney et al., 2012a). As shown in Fig. 2, rind thickness on the subject clast is close to the mean thickness, and representative of the entire population of 50 clasts measured in the field. Two main weathering zones are evident in the macrophotograph (Fig. 2), three if the thin carbon–Fe-rich layer (0.2 μm) is taken into account. Below the surface of the carbon-rich zone, the outer zone of approximately 1000 μm thickness merges with the inner zone of almost equal extent, the latter making a sharp contact with the inner fresh lithic area. These zones, in microcosm, mimic almost exactly the character of the resident paleosol with which the clast is

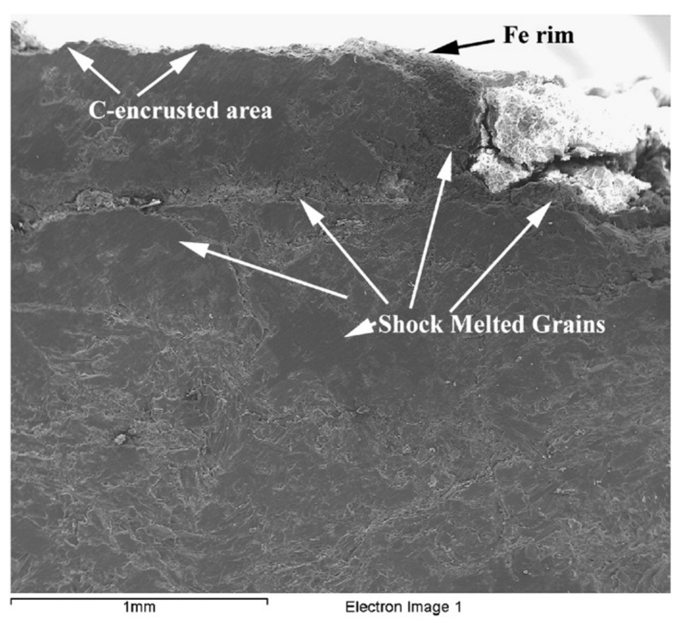

Fig. 3. Image of the rind surface, outer and inner weathered zones showing prominent crack structures filled with fragmental impact material, areas of shock-melted grains and C-encrusted surface.

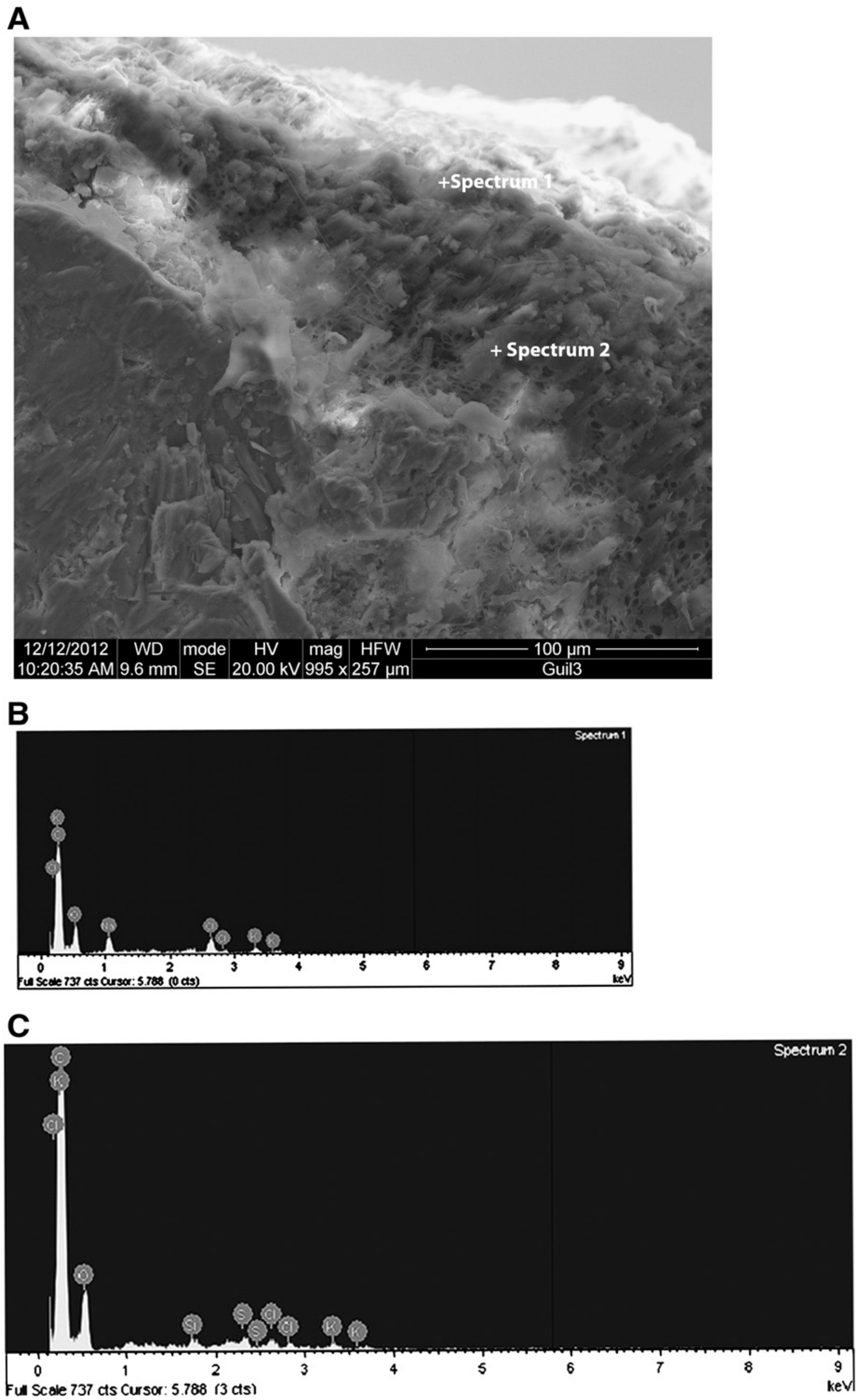

Fig. 4. Outer rind area. A, Carbon-encrusted quartz fragment in highly brecciated area. The dark area, generated by low atomic number material, is mostly carbon; B, EDS spot check (Spectrum 1) showing C and minor Cl, K and Na; and C, EDS spot check (Spectrum 2) revealing minor Si, Cl, K and high carbon. Given the 20 keV accelerating voltage the carbon must be over a micron in thickness.

associated, and the Ah/Bw/Cox/Cu horizon succession approximating the C-rich surface, outer zone, inner zone and fresh lithic core; a near perfect match on vastly different scales.

The SEM image (Fig. 3) provides a low magnification scan on a polished section of the rind with the approximate boundaries of the weathering zones marked. Cracks, both normal and parallel with the rind surface, are evident in the imagery, many rather large, up to 150 μm in width and containing fragmental, brecciated and shock-melted material. While the two main weathered zones have similar crack structures, the outer zone closer to the rind edge contains a greater frequency of partial and fully shock-melted minerals, partly composed of quartz and mainly comprising augite–diopside–hedenbergite species of pyroxene. Random albite of fine silt size is also found within the rind, and is presumably of aeolian origin, although definitive aeolian microtextural signatures could not be obtained.

Within the outer zone and near the carbon–Fe encrusted surface, tonal contrasts indicate a variable but high concentration of carbon (low atomic number = dark surfaces) as shown in Fig. 4A. The EDS

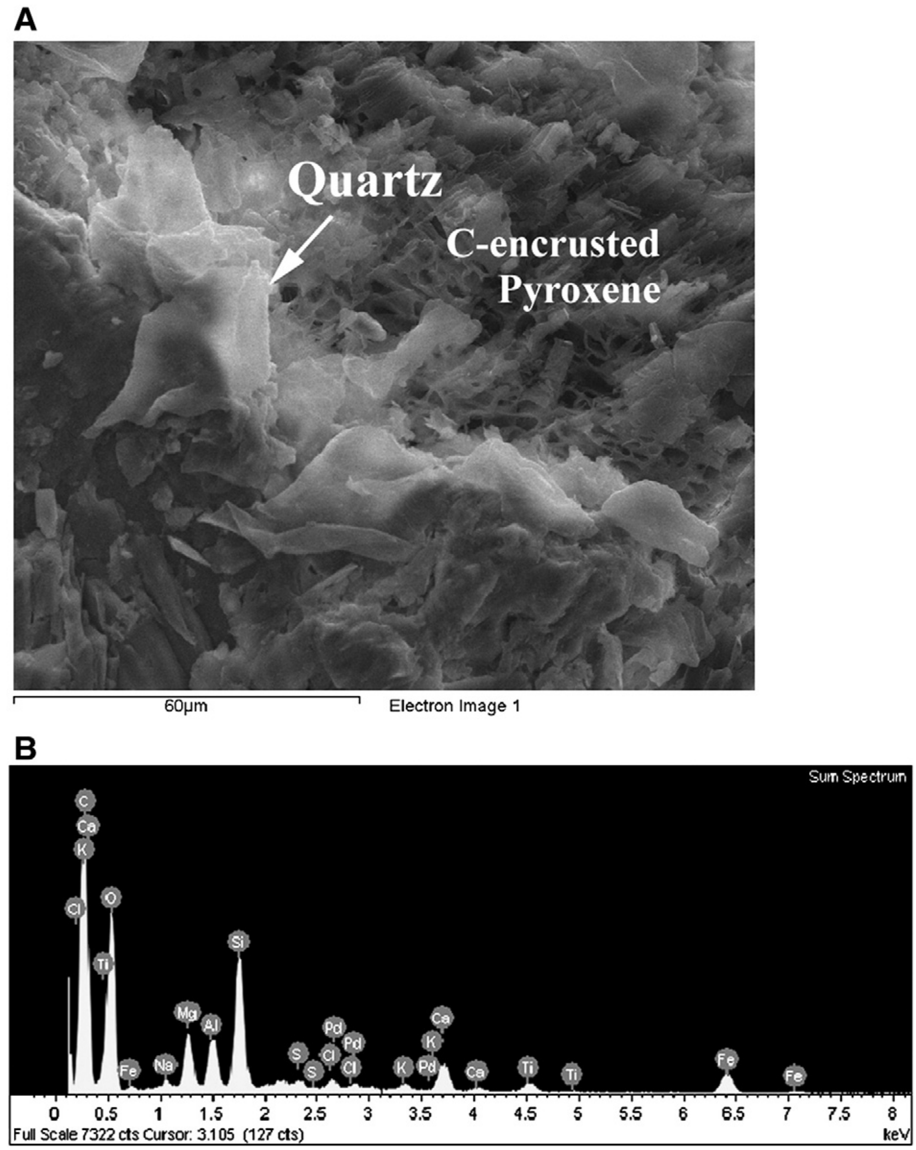

Fig. 5. A, Partial and fully shock-melted grains in the outer area. The partially melted quartz and pyroxene are highly contorted and twisted from release of excessive heat, presumably from an incandescent cloud; B, EDS of the entire image which matches tonal contrast. Light area is Si, the remainder of various species of pyroxene. The dark area is carbon rich, sometimes with encrustations exceeding 1 µm. Chlorine and S could be by-products of the metabasalt or imports with aluminum glass from the cosmic airburst.

in Fig. 4B indicates mainly C, with minor concentrations of Na, K and Cl, the latter element possibly from the cosmogenic cloud that impacted the surface. In this instance the carbon may have a thickness of near 1 µm which may explain why no clear mineral host can be identified. Below the carbon-encrusted fragment in Fig. 4A, the highly brecciated area of the outer rind is shown in great detail with tonal contrasts more pronounced and partial melted grains alternating with fully shock-melted mineral fragments. The EDS (Fig. 4C) of one grain indicates possible quartz coated with C and very low concentrations of Cl, K, and S, the Cl and S presumably sourced from the incoming incandescent cloud or from the country rock. Various degrees of melted mineral species as identified in Fig. 5A depict what appear to range from partial melted/contorted to fully shock-melted material. The shock-melted quartz shown here has been subjected to intense heat (Mahaney, 2002), whereas tectonically shocked quartz (Gratz et al., 1996) is different, being subjected to sustained high pressure, producing crystallographically-oriented pdf's, generated by high-strain-rate shock waves at pressures of >12 GPa. While we encountered considerable shock-melted material we did not observe pdf's. The EDS (Fig. 5B) of the full image in Fig 5A shows high Si and C. The light area in Fig. 5A is presumably contorted and melted quartz and the area right of center and upper right shows lower Al, Mg, Ca and Fe related to carbon-encrusted pyroxene species. The low concentration of Ti is probably related to the country rock.

The area below the brecciated outer rind surface shown in Fig. 6A is composed of cracks filled with partially melted and contorted grains of quartz, pyroxene and olivine that appear to have been partly fluidized and forced into place under extreme heat and pressure. The cracked material ranges from intact brecciated grains from the outer rind area to shock-melted grains and the channel sides appear torn and ripped in places. The tonal contrast suggests hematization, which is common with invading lavas producing a contact zone. The EDS taken as Spectrum 1 between two parallel crack systems yields an olivine composition, with some Si, no Al, and some Ca, Fe, Br and Mg. The Br is probably inherited from local vegetation or lichen growth. The area within the upper crack system (Fig. 6C) yields Spectrum 2 taken on a grain with a dark tone, the EDS of which (Fig. 6D) yields high Si, Al, Mg, with some C, small Fe and minor Ca, K and Cl, suggestive of augite. A second image showing details of the crack system (Fig. 6E) gives a similar chemistry of Si, Al, high C, and minor Ca, Cl, Fe and Mg. Augite seems to be the dominant pyroxene contained within this crack system, with individual grains modified to varying degrees.

The contact between the inner weathered zone and the fresh core is shown in Fig. 7. The lower rind area exhibits high crack propagation from impact as well as considerable tonal contrasts, and the light fringe areas on grains are probably outlining high secondary Fe.

5. Discussion

Similarities exist between the black mat described in the Northern Andes (Mahaney et al., 2008, 2010) and the impact grains described here. These include intense brecciation and internal fracture patterns in both sample suites, with the degree of brecciation of about equal intensity in both the Andean and Alps samples. Brecciation may be more a function of impact rather than heating, incoming particulate matter releasing enormous kinetic energy producing disruption of mineral fabric on a large scale to a rind depth of 1000 μm, and crack propagation to greater depth. Microfracture patterns in the samples are either parallel or normal to the surface, the pattern possibly related to impact energy or to variable energy cone vectors. This microfabric pattern is similar to that reported by Mahaney et al. (2011b).

Black mat material in the Andean samples ranges from fibrous carbon-rich material with accessory Fe and Mn to glassy C-rich spherules, the latter often welded into grain surfaces and covered with layers of Fe and Mn. Carbon is fixed on topographically irregular grain surfaces and is often welded to mineral grains and complexly intergrown in some cases. Brecciated microfeatures in some areas of the Andean samples radiate out into zones of high frequency microfractures produced either by mass impact or high-temperature soot release from wildfires (Stich et al., 2008), or heat release from an incandescent cloud. As observed with the Alps samples, heat-induced microfractures are random, and with similar spacing as in the Andean examples, but with cracks wider than in the Andes. As with the black mat Andean samples, the Alps microfractures are

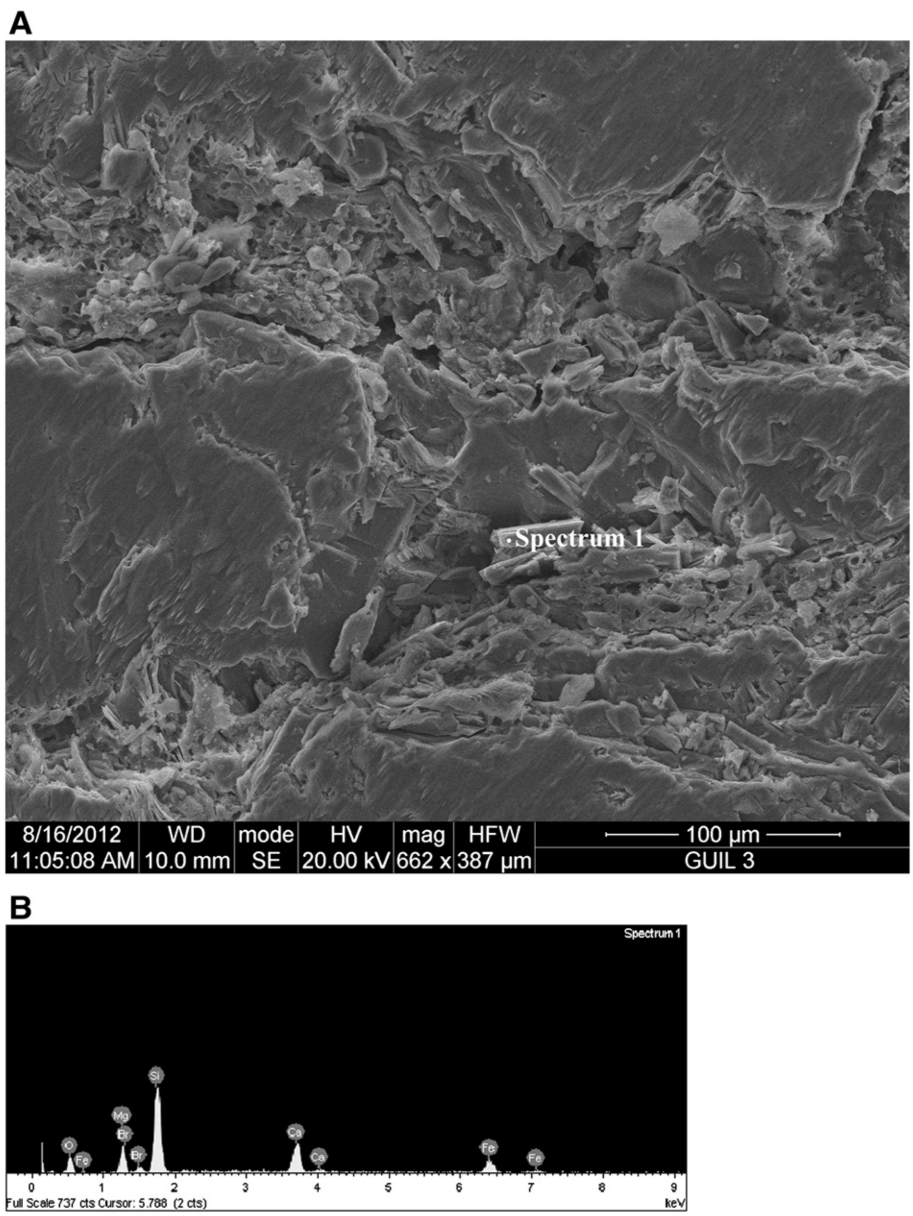

Fig. 6. Inner rind area. A, Crack zone with diopside–hedenbergite grains partially melted; B, EDS of selected material; C, Melted augite; D, EDS of C; E, Augite fully melted; and F, EDS of E.

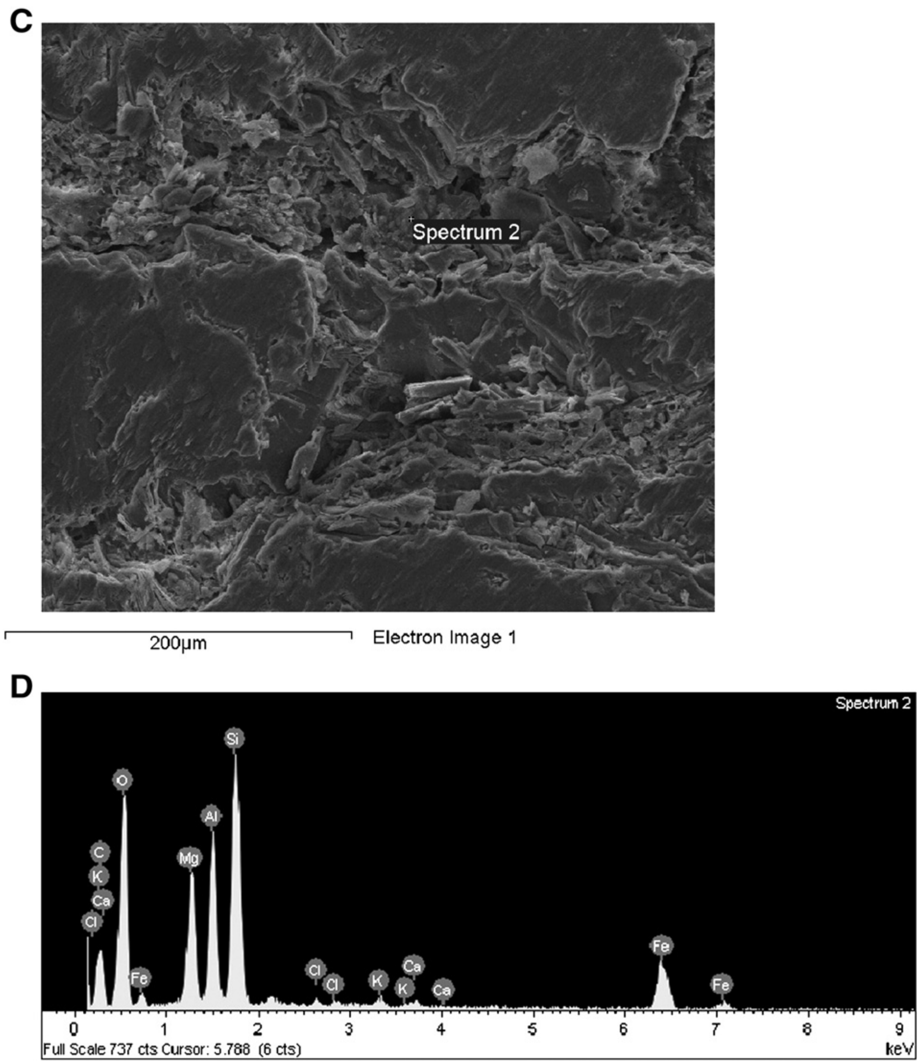

Fig. 6 (*continued*).

closely packed into high density areas which may be vibration-generated microfeatures, the actual troughs filled with shock-melted material, appearing to have been generated as viscous streams shortly after impact, cooling rapidly thereafter.

Crenulated or scalloped grains shown in Fig. 4A carry a thick C-coating but also contain some Al and Cl. The Al, though scarce in the local pyroxene-rich lithology, could be scavenged from other country rock minerals but the Cl, while unexplained, could either be a volatile element in the country rock, or related to aluminosilicate glasses with an interstellar origin (Stebbins and Du, 2002). This occurrence is similar to what has been previously reported in the Andean black mat by Mahaney et al. (2010).

The black mat Andean data and the Alps examples reported here thus far support a kinetic theory of mass impact of particles in an incandescent carbon-rich cloud which produced brecciated surfaces as well as a high frequency of closely spaced microfractures and larger crack systems. Brecciation itself may depend upon grain-to-grain collisions at extremely high velocity, although with variable masses involved. Incoming ejecta might be expected to have consisted of very fine sand to silt particles; the resident coarse clastic pebble and cobble size material recording the event receiving the production of carbon encrustations, partial and shock melting of host grains and propagation of micro- and macro-crack systems acting as conduits of viscous material. The welded character of C-bonded encrustations argues for extreme heat at temperatures much higher than 900 °C, apparently high enough to melt pyroxene, but not high enough to shock-melt quartz. The exact temperature of incoming ejecta is unknown but to weld carbon to grain surfaces without melting quartz would require between 900 °C and 1670–1713 °C, of β tridymite and cristobolite, the latter estimated melting temperature somewhat higher than α quartz, estimated at $<$1670 °C (Frondel, 1962; Deer et al., 1966).

Possible alternative hypotheses to explain black mat sediment have focused on the nature of the placon (aquifer) the black mat often resides in at various sites in the Andes (Mahaney et al., 2008. Explanations requiring flux of water in an aquifer require chemolithotrophic bacteria (Bougerd and De Vrind, 1987) and alternating redox conditions favoring retention of C, Mn and Fe. This hypothesis follows the view of some (Quade et al., 1998) that the black mat is the product of subsurface drainage accumulation of organic and associated oxides and hydroxides without any cosmic connection. Since bacteria were not detected in the analysis presented here it would seem that alternating redox conditions do not apply in this instance, nor were any expected given clasts embedded in moraine surfaces. The null hypothesis for a terrestrial origin lies in the presence of high frequencies of breccia, thick carbon encrustations sometimes intertwined and welded with mineral grains, extensive microfractures and excessive crack propagation inward toward the fresh lithic core. The cracks, filled with shock-melted grains,

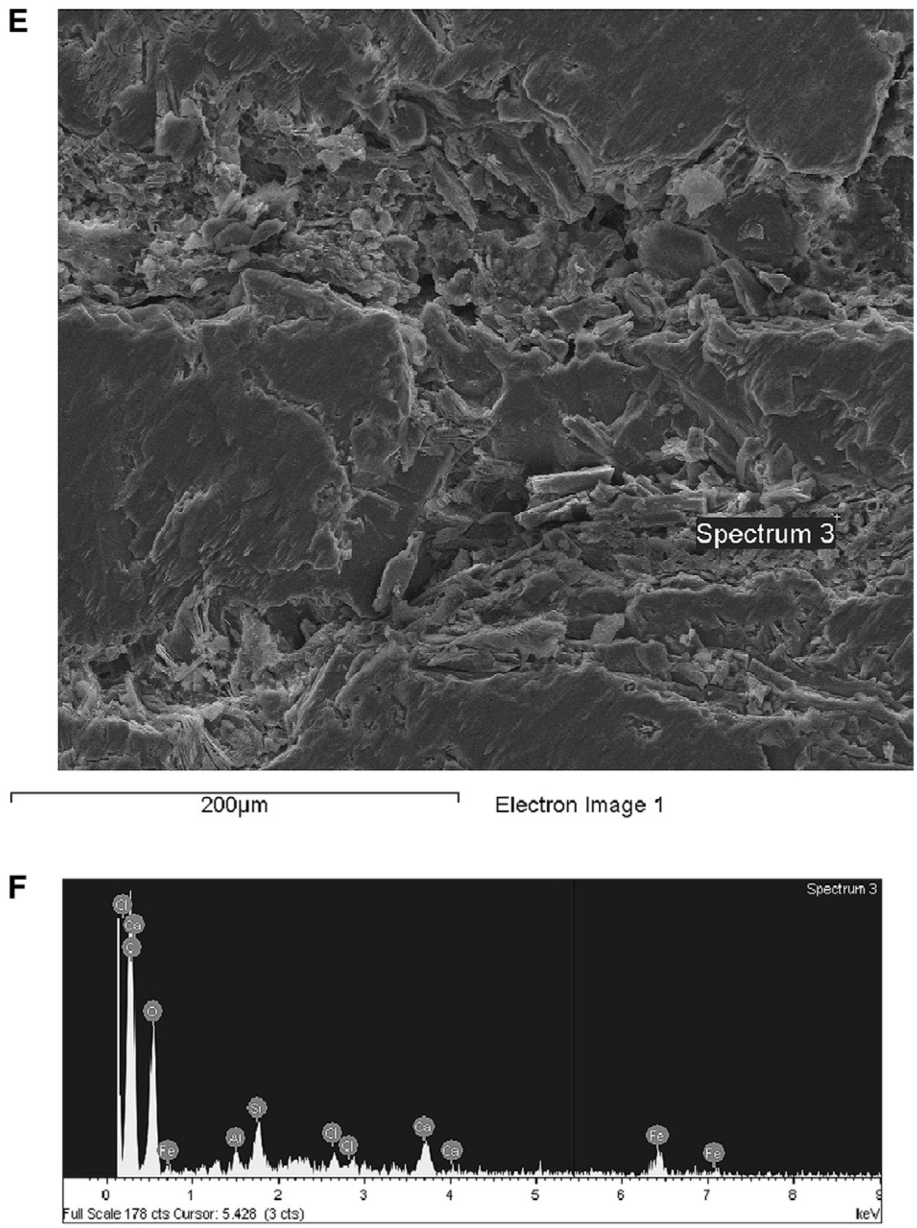

Fig. 6 (*continued*).

are not manifestations of normal terrestrial processes. Admittedly the lack of nanodiamond, pdf's, platinum and Be isotopes softens the cosmic hypothesis but then the distance between primary impact in southern Canada and the terminal zone of ejecta in the Alps leaves open the question of dispersal of impact material with increasing distance from the Laurentide Ice Sheet. The spread of ejecta outward from the blast site is hardly expected to reach the receiving area (ejecta reach about five crater radii from an impact; Boslough, 2012), but a detached part of the incoming cosmic vehicle could reach the Alps, as is interpreted for other airbursts which reached the French coast, The Netherlands (Kloosterman, 2007), Abu Hureyra, Syria, and Central Asia (Bunch et al., 2012).

A second alternative hypothesis might question the lack of C-rich spherules in the samples under discussion here and the lack of chondrules as an important argument against a cosmic origin. Comparison of the C-rich spherules in the Andean black mat with similar samples analyzed by Firestone et al. (2007a,b) shows more similarities than differences. If one were to consider the C-spherules as less dense than those studied by Firestone et al. (2007a) one might also argue that the Andean specimens could have weathered extensively or suffered from distance traveled. While no carbon-rich spherules were identified in the Alps samples it is possible that they may have been vaporized or fallout may have preceded terminal impact. Additional analysis may yet reveal the presence of microspherules that would help to bolster a cosmic origin.

A third hypothesis could be mounted to challenge our conclusions that the fired rock underwent extremes of heat without impact, which is absolutely correct. However, while low and high temperature firing experiments have produced microfractures around grain edges of quartz producing a micro-brecciated effect, grains in the Andean black mat bed (Mahaney et al., 2010, 2011a,b) exhibit a fusion of carbon with quartz. Moreover the twisted/contorted nature of select grains in both the Andean black mat and the Alps samples indicates something more than a low grade bush fire or higher grade lightning strike occurred at the site. Even considering the partial evidence presented here, a cosmic connection offers the best explanation.

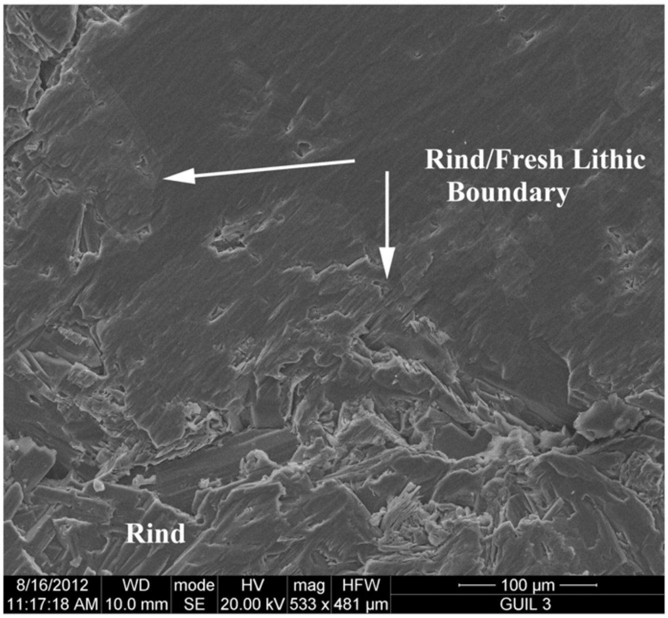

Fig. 7. Inner rind contact with fresh lithic core rock. Striae-like features are the result of milling the sample to produce the polished specimen. Propagated cracks even at this depth in the rind are near horizontal and filled with shock-melted grains that may have been made viscous with released heat from a proposed incandescent cloud.

A fourth hypothesis might be that the cracked clasts could be the product of simple physical weathering but if this were the case it would be expected that clasts of YD age, of a similar lithology, would carry similar highly brecciated surfaces connected to internal crack systems. Oxidized rinds lacking extreme brecciation on the YD clasts, and a high frequency of internal cracks and melted/contorted minerals in the LG moraine, are best explained by the high temperature and pressure of a cosmic airburst.

Firestone et al. (2007a) proposed that the black mat impact (YDB) generated microspherules, the combined effect of impactor ablation and high-temperature melting of terrestrial target rocks. In this paper, we discuss the latter possibility, the microspherules yet to be discovered. An extraterrestrial (ET) impact event, presumably from a cometary vehicle breaking up over southern Canada, as proposed (Napier, 2010), is expected with an airburst to produce a widely turbulent impact plume or fireball forming an incandescent cloud containing vapor, melted rock, shocked and unshocked rock debris, breccia, microspherules, and other biotic and abiotic impact materials resident in the target area, in this case part of the Alps.

Commonly, melted siliceous glass (lechatelierite) is formed on impact when plume temperatures reach 2200 °C, the boiling point of quartz. Lechatelierite is not a volcanic product nor can it be produced by metamorphic processes, but it is a product of lightning strikes which also produce fulgurite. That lechaterlierite and fulgurite were not observed in the results reported here probably suggests that the firing temperature did not reach the 2200 °C level.

With the generation of an airburst, convective cells may form in an instant at temperatures similar to or higher than the photosphere of the sun (Bunch et al., 2012). Materials within the fireball interact briefly with cloud materials in vapor or molten phases, some of which may be ejected to interact with the country rock. Fireballs produced by airbursts have limited life spans, perhaps tens of seconds, but may reach high into the atmosphere affecting the cosmic ray flux allowing isotopic changes at the surface. Interaction of particles within the plume may involve repeated collisions, the sum of which produce mineral accretions and collision microfeatues including regmaglypts, which in this case could relate to melted fragments of quartz, pyroxene and olivine. Although microcraters in the landscape are sometimes by-products of cosmic airbursts (Bunch et al., 2012), none have been found thus far.

6. Conclusions

Our analysis of rinds in designated Late Glacial moraines described here indicates fragmental mineral structures, carbon encrustation on and within grains, various degrees of grain melting and presence of Cl in grain coatings are similar to cosmic-impacted material and cosmic airburst impacts at 12.9 ka, as documented in the Andes. While we cannot conclusively date the LG and YD moraines described here, relative age assessment suggests they were emplaced at the end of the last glaciation. The microscopic grain analysis presented here requires more than normal chemical weathering to achieve mineral cracking, fragmentation and melting, as detailed in the present database. While lightning might fragment and carbon coat rock material it would not be expected in a first seral stage wet tundra to release high concentrations of carbon such as are identified here, and to weld it onto mineral fragments. While the resident site is far from the center of a high-energy airburst impact hypothesized to have occurred over southern Canada, the available data strongly suggest that an enveloping carbon- and volatile-rich cloud, presumably generated by airburst of a comet fragment at the YDB, reached the European Alps.

One may never prove conclusively that the black mat exists in the French Alps but an impact did occur within the Late Glacial time frame. It appears that the impact did not kill the megafauna that existed elsewhere in Europe; the species extinction that forms an important part of the YDB stratigraphy in North America is so far undocumented in the Alps. Certainly all local flora and fauna perished with the event, the impact of an incandescent cloud terminating life in the area of the Guil Valley. Locally, an enormous shock wave coupled by heating and fires, possible earthquake, and extra-hurricane winds, with incalculable tonnage of debris thrown everywhere, would have created darkness and cooler temperatures for an unknown length of time. Herein lay the crux of the controversy. Was the global effect of the impact sufficiently long-lived to have generated the Younger Dryas? The evidence presented here provides only part of the story — particle-produced propagation of cracks, generation of pronounced breccia, melting of quartz, olivine and pyroxene with minor S and Cl as possible carry-over byproducts of the impact. Sulfurous aerosols may have cooled the Earth for years. Continued existence could not have been easy for surviving species, at least in the Americas and possibly over much of the rest of the world. Because the proposed comet break-up left the Taurid complex, which still lies with Earth's orbit, it is likely that comet fragments may have impacted the planet for centuries, thus maintaining the negative temperatures required to maintain positive mass balances in YD glaciers.

Further research needs to be carried out to assess other sites of Late Glacial age in the Alps, preferably with a mix of LG and YD moraines to corroborate the findings presented here.

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