



Late Pleistocene Glacial-Paleosol-cosmic record of the Viso Massif—France and Italy: New evidence in support of the Younger Dryas boundary (12.8 ka)

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Abstract

Mount Viso (3841 m asl), one of the highest mountains in the Western European Alps carries not only a glacial record following the end of the last glacial (Late Glacial-LG), but also a cosmic airburst record at approximately ~ 12.8 ka, presumably the black mat, that adds to a worldwide record of biomass burning which is considered to have triggered the Younger Dryas (YD) cooling episode. We combine the stratigraphic evidence of staggered Late Glacial retreat on both sides of the continental divide—faster in the upper Guil, possibly slower in the upper Po valleys—followed by superposed YD moraine overlapping LG in France, and stillstand of LG with overlapping YD in Italia with recovered cosmic evidence. Previously, we studied selected areas on the Viso massif, but here we expand on newly combined stratigraphic-cosmic airburst evidence, the latter lying in an uneven distribution of welded, melted and air-quenched clasts of pebble to sand-silt size in paleosols, all of which carry variable high to low REEs, high base metals, partial Pt and Ir coated surfaces indicative of nuclear-cosmic events. One of the outstanding conclusions of this research is the indisputable close correspondence of widespread cosmic airburst evidence with the YDB (Younger Dryas boundary) and onset of the YD. Thus, a test of catastrophism, firmly embedded in surficial sediment, yields some important underpinnings of Earth's climatic history.

Keywords Alpine weathering · Glacial stratigraphy · Cosmic airburst

Introduction

The Guil Glacier (Fig. 1a, b, expanded in Fig. 2a, b), and the Po glacier to the east (Fig. 2c), two of the most important catchments in the Western European Alps, underwent

insolation-forced recession starting ~ 15 ka (Cossart et al. 2010; Warner 2012). Glacier recession was rapid, leaving only islands of ground moraine in the lower reaches of both catchments, stillstand moraines above 2200 m asl (above sea level) on the east flank, 2400 m asl on the west. The slight difference of elevation in both catchments attests to a slow-down of glacial recession at some point during the Bølling-Allerød retreat phase during the LG, followed by a cosmic airburst (Mahaney and Keiser 2013; Mahaney et al. 2013a, 2016a, b), considered coeval with the widespread YDB (Younger Dryas boundary) event of 12.8 ka (Kennett et al. 2015). As in other locales worldwide, no impact crater has been identified; hence, a fragmental airburst is considered the likely body causing the event. In some cases, this event produced a dark layer in sediment successions, often called the “black mat” (i.e., as in the Andes, Mahaney et al. 2013b). In the Alps, no such micro-feature has been found, the cosmic evidence residing in surface clast rinds and in paleosol matrix sediment.

The Guil River catchment (Fig. 1b), aligned along a linear fault with runoff channels from the Continental Divide

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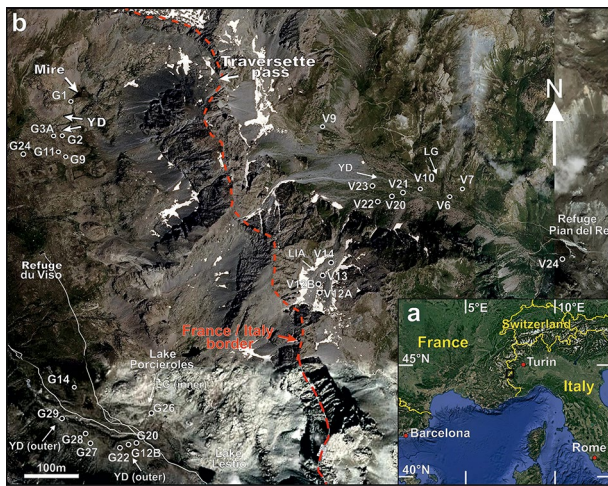
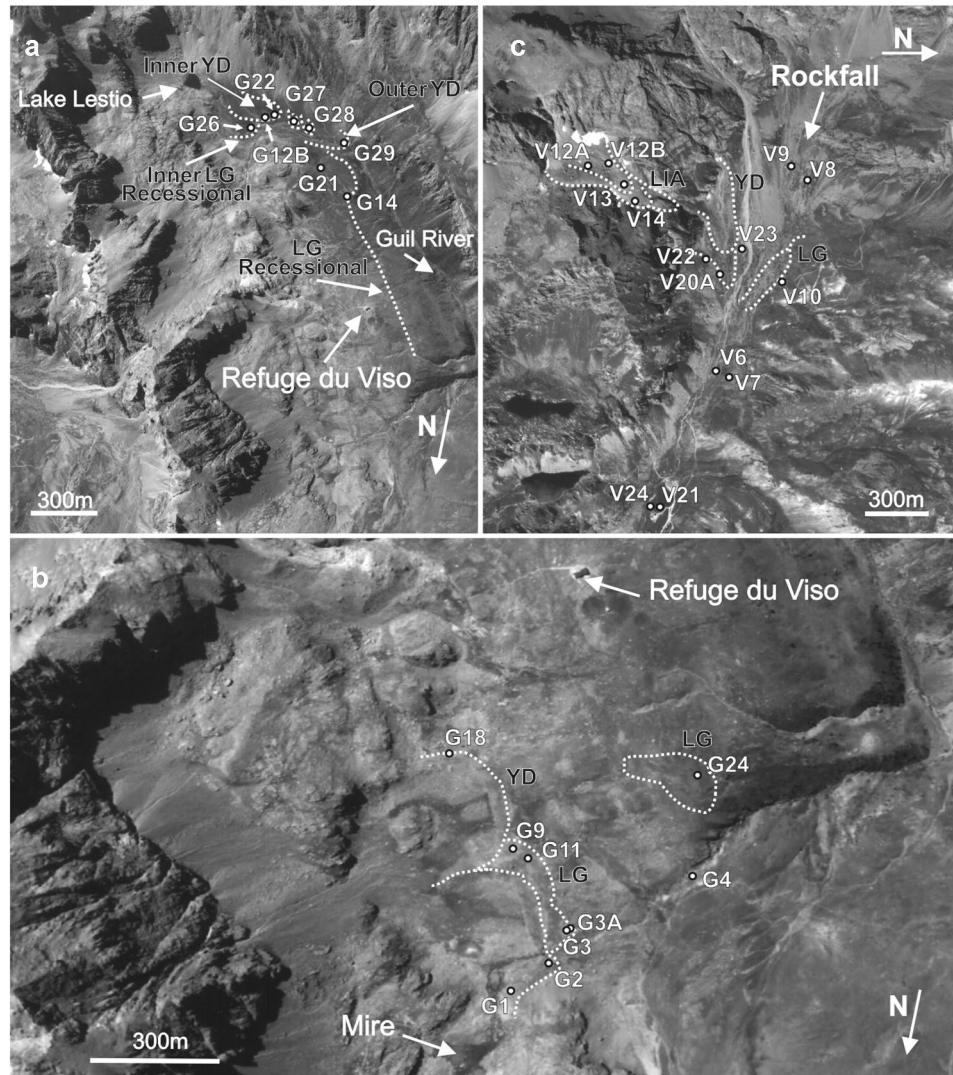


Fig. 1 a, b Location of sites in Guil South, Guil North and the upper Po Basin, Mt. Viso on the France-Italian water divide

west to the Durance River, eventually drains into the Mediterranean Sea. To the east, from its headwaters (Mt. Viso, 3841 m asl) in the upper Po catchment, runoff follows a near linear course of ~650 km, from the Alps across northern Italy to the Adriatic. While both drainages responded to insolation warming from ~15 ka through the LG, recession stopped at the end of the Allerød, circa 13 ka, following stillstand events of unknown duration. It is within these stillstand deposits that the YDB evidence of a cosmic airburst is found distributed in weathering rinds documented by Mahaney and Keiser (2013) and Mahaney et al. (2016b), and in paleosols (Mahaney et al. 2013a), all in the Guil N catchment. As receptors of cosmic input, rinds are fixed entities in moraine/mass wasted surfaces, and represented by the hundreds of samples analyzed, the outer rind is impacted by PT forces to depths of ~700–800 μ m. Subsequent to airburst weathering, fluids penetrated deeper to ~3 mm at the rind/rock contact. Soils in early weathering stages affected by the airburst would have been subject to grain loss and/or input,

Fig. 2 Surficial deposits. a Guil south; b Guil north; c upper Po catchment



horizon to horizon, with later relocation of affected material by continual re-distribution in developing paleosol horizons.

Glacial retreat during the Bølling-Allerød interstadials deposited coarse clastic ground and lateral moraines exposed to warm/humid climate conditions described by Mahaney et al. (2016a), providing host material with variable mineral contents typical for weathering and soil development to ensue (Mahaney et al. 2013a). The climate situation changed abruptly after ~12.8 ka (i.e., LG termination), with the onset of YD cooling, accompanied by positive glacial mass balances in the upper valleys, leading to renewed glaciation, ice advance, and moraine production, including push moraine complexes in some areas. Because the YD is the latest Pleistocene climatic reversal, occurring with termination of the initial warming during the LG (Ralska-Jasiewiczowa et al. 2001; Gibbard 2004), moraines and associated deposits documenting the event need to be studied for composition and comparison with earlier LG deposits. Previously, our research centered on Guil North (see Fig. 2b), now expanded to include G-South and Viso (Upper Po).

Here, we uniquely combine the LG, cosmic-YDB, YD evidence of the Viso Massif forward to enhance the punctuated glacial record of the Western Alps and to compare the cosmic evidence with sites and sediment records worldwide. Also, we critically examine the possible cause of the YD. Was the YD climatic anomaly tied to large-scale marine currents and freshwater outbursts (Teller et al. 2002), variable atmospheric gas content (CO₂), solar activity (Kudryavtsev and Dergachev 2021), or the much-debated comet impact/airburst termed the black mat (Firestone et al. 2007)? Thus, the introduction of a cosmic hypothesis to what some consider a terrestrial episode in earth's climatic history.

Regional geology

Bedrock geology

The pre-Late Glacial geology of the upper catchments for the sites (Fig. 2a–c) under discussion was extensively eroded by Pleistocene glaciation, leaving a series of high cliffs, bedrock steps, and occasional whalebacks fashioned by meltwater release and large cirques below the Col de la Traversette at 3000 m a.s.l (Fig. 1b). This landscape, carved into the Alps Piedmont zone summarized by Tricart (1984) and Tricart and Schwartz (2006), contains a mixed large volume of metamorphosed marl-rich sediment highly deformed into the so-called “schistes lustrés”, which contributed minerals to both the Late Allerød and YD sediments discussed here. These soft sediments carry enclosed beds of variable meter to kilometer size lithologies of variable weathering resistance, including gabbro, basalt, meta-basalt (Tricart et al. 2003), serpentized peridotite, and dolomite. The schistes

lustrés mineral zone by itself consists of sedimentary and metamorphic rocks derived from Tethyan oceanic sediment, including widespread ophiolites. The Mt. Viso and the Col de la Traversette rock suites are composed of mafic and ultramafic rocks originating from this oceanic lithosphere, which produced lithologies strongly deformed and metamorphosed under eclogitic-facies conditions (Schwartz et al. 2000).

Late Pleistocene geology

Retreat of Late Glacial (Würm, Weichselian) ice in the Durance catchment, from its terminus near Sisteron (44° 20' N, 5° 93' E, 448 m asl) (Warner 2012) to the upper Guil River basin/continental divide was without a punctuated withdrawal, there being no recessional moraine markers at lower elevations, retreat tuned to slow warming through the two interstadials—Bølling-Allerød—leading up to the YD. If stillstands of Late Glacial (mid-LG) ice did occur below ~2400 m asl (Guil N–S and 2200 m in Upper Po), they were short-lived and destroyed by meltwater. Both catchments in their lower reaches present with steep canyons—Combe de Queyras in the Guil and unnamed deep channel in the upper Po—attesting to movement of vast volumes of meltwater to lower elevations. LGM (Last Glacial Maximum) ice in the Po basin was confined to the lower canyon below the town of Crissolo (1919 m asl) as identified by Soldati and Marchetti (2017). Other workers (Cremaschi et al. 1990; Cremaschi and Van Vliet-Lanort 1990) mention only loess stratigraphy near the Po canyon mouth, the only ‘LGM boundary’ mentioned by Balestro et al. (2013) is marked with alluvial fans, not moraines. Thus, the glacial stratigraphy of the younger interstadials/stadial of the last glaciation, leads up to the Neoglacial (LIA), envelope elevations above 2400 m, all in Guil N-S, and 2200 m asl in the upper Po. With the absence of moraines in the lower canyon of the upper Po River, we place the terminus of the Po ice during the LGM near the town of Chisola at 44° 59' 42 N; 7° 40' 25E, elevation 683 m asl, some ~240 m higher than on the western slope.

The upper Guil catchment is the type locality for the cosmic airburst, presumed to be the black mat, formed at or close to the Younger Dryas boundary (YDB) in the European Alps at 12.8 ka. Evidence for cosmic-affected sediment was first uncovered during analysis of weathering rinds (Mahaney and Keiser 2013; Mahaney et al. 2015) in Guil North (Fig. 2b). All three catchments southern, northern and eastern (Fig. 2a–c) carry a two-fold sequence of Late Glacial (LG) and Younger Dryas (YD) deposits, all above 2200 m asl. In both west and east catchments, LG moraine lies, in part, buried by younger moraine considered to be of YD age, assessment based on moraine superposition (Fig. 3a in the Guil valley). Along the upper Po catchment,

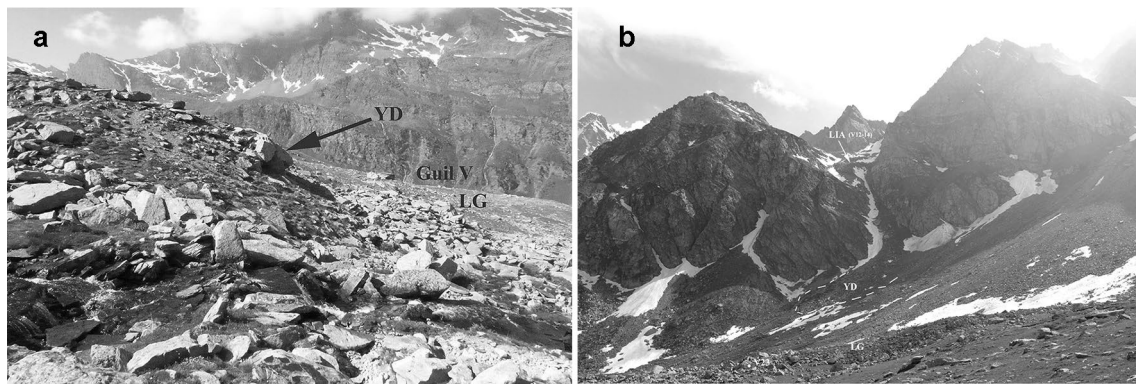


Fig. 3 **a** Superposed moraines (LG-YD) in Guil north, France; **b** LIA moraines in couloir, northeast flank of Mt. Viso. The water divide (France-Italy) is in the skyline

above 2200 m asl, the valley floor is laced with LG and YD moraine (Figs. 2c and 3b), and various mass wasted deposits consisting of talus, rockfall and outwash. In only one single couloir issuing from the northeastern slopes of Mt. Viso, a sequence of YD deposits can be traced to (LIA) moraine issuing from the continental divide (Fig. 3b). Both the LG and YD deposits carry suites of paleosols marked by similar depths of ~45–50 cm, all with Ah/Bw/Cox/Cu profiles termed Cryochrepts in the US Soil taxonomy (NSSC 1995).

Prominent recessional moraines are found either nested at a single location within the Guil drainage, approximately 1 km (~2500–2400 m asl) down valley from the drainage divide at ~3000 m asl at Col de la Traversette (Fig. 1b). One of these LG recessional moraines (principally sites G3, G9, G11, Figs. 1b and 2c) was overrun by a re-advance, presumed to be of YD age (comprising sites G1 and G2 in the Guil catchment). Because weathering characteristics of surface clasts and paleosols of LG and YD age are similar (Mahaney and Keiser 2013; Mahaney et al. 2013a), they must have ages separated to the order of centuries or possibly up to a millennium. Despite the lack of bog deposits suitable for coring and collection of bottom sediment in LG deposits, to provide minimum ^{14}C ages on cessation of moraine emplacement, obtaining absolute radiocarbon dates is not possible. However, bog deposits behind the YD deposits, at site G5 (Fig. 1b) provide a number of dates of middle to late Holocene age, much younger than the YD. In the upper Po valley, YD moraines merge with LG moraine, the separation situated within younger erosional channels indicating that any superposition of deposits was lost with fluvial activity. The age of the YDB within the LG sediment complex can only be determined by ice retreat through the Allerød, subsequent moraine stillstand providing only a few centuries of soil development prior to the cosmic event (Mahaney et al. 2016a).

Above the superposed LG and YD moraines in the upper Guil valley (Guil N), slopes of 10–20° lead up into

a prominent cirque below the Col de la Traversette, largely covered with LIA rockfall and talus/protalus cover (sites G6, G8 and G10 in Mahaney et al. 2016a). The Traversette cirque floor presents with exposed bedrock in few places and lacks exposed ground moraine making it difficult to determine if LG ice receded into the Traversette cirque prior to the YD advance. Thus, it is unequivocal that YD ice advanced to 2450 m asl, overrunning inner LG recessional deposits in the process, occupied a stillstand position for an undetermined time, and given normal ages for the YD, not much beyond more than a millennium.

Materials and methods

Field analysis

The Guil and upper Po river field area was mapped from 1:20,000 air photography with deposits selected on the ground based on representative soil/paleosol profile expression (Fig. 1b). Over the period 2002–2017, sections (profiles) were excavated to depths up to ~0.8 m, as required. Profiles increase with age, from the youngest LIA (Little Ice Age) to older LG surfaces, as weathering and time modify depth and degree of profile horizonation. Soil/paleosol horizon (bed) description follows the NSSC (1995), with the exception of 'Cox' designations based on Birkeland (1999) where below solum weathering has produced secondary oxides/hydroxides, and where unweathered sediment carries a 'Cu' identification (Hodgson 1976). Where dark brown/black colors occur, the 'Ah' designation is applied to designate appreciable humus (Canada Soil Survey Comm. 1998). Soil colors follow the color chips in Oyama and Takehara's (1970) soil manual (equivalent to Munsell color sheets). In all cases approximately 300 g of sample was collected from sections for particle size, clay mineral, geochemical, and microscopic analyses.

Laboratory sediment analysis

Collected sediment samples were air-dried to remove field moisture and treated with H_2O_2 to oxidize at least some of the organic content. For particle size analysis, samples were wet sieved to separate the sand fraction and the $< 63 \mu\text{m}$ fraction was subjected to analysis by hydrometer (Day 1965). All particle grade sizes follow the Wentworth Scale, excepting the clay/silt boundary of $2 \mu\text{m}$ which follows the U.S.D.A. Geochemical composition was determined using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES), using a Varian Liberty Series II instrument, with $\sim 1 \text{ cm}^3$ bulk samples first subjected to an aqua regia digestion. Rare-Earth Elements (REEs) were determined for most horizons by instrumental neutron activation analysis (INAA) performed on the $< 177 \mu\text{m}$ (80 mesh) fraction at Activation Laboratories, Ancaster, Ontario, Canada. Selected samples were analyzed by ICP. The main oxides of some samples were analyzed by X-ray fluorescence spectrometry (XRF) at the Department of Geology, University of Tartu, using a Rigaku Primus II spectrometer. Crustal averages for macro-micro- and REE elements are based on Rudnick and Gao (2005).

The clay fraction was studied for mineral composition by means of powder XRD using a Bruker 8D diffractometer with Ni-filtered $\text{CuK}\alpha$ radiation. Scanning steps for oriented samples were $0.02^\circ 2\theta$ from 2 to $55^\circ 2\theta$. A semi-quantitative mineral composition was determined from peak integral intensities of chlorite, illite-vermiculite, mica + illite, talc and smectite, multiplied by factors of 1, 0.35, 2, 1.4, 0.2, respectively (Kalm et al. 1997). The Chemical index of alteration (CIA) was calculated by molar ratio of $[\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100$, where CaO^* is the amount of CaO combined in the silicate fraction from Nesbitt and Young (1982). The dimensionless number (0–100) indicates relative degrees of weathering.

Following the physical–mineral–chemical and geochemical airburst evidence, we tested for microbial anomalies in some nine paleosol sections in the upper Guil catchment (See Fig. 1B; Mahaney et al. 2013a). We previously demonstrated using density gradient gel electrophoresis (DGGE) analysis of 16S rRNA genes from metagenome soil DNA extracts that eubacterial populations of LG age in section G3 (correlates to site G3A; Fig. 1b) showed very different profiles compared to the G1 and G2 YD profiles shown in Fig. 1b. From this, we might assume microbial anomalies exist in other paleosol horizons or even in complete sections. If microbes exist with varying metabolic needs, we can expect this to be reflected in 16S rRNA genes from certain organisms because we know different bacteria genera have produced different metabolic approaches to survival. Further detailed functional gene analysis will focus on REEs as electron acceptors, a future approach needed to determine

if certain bacteria populations survived the airburst evolving up to the present.

Results

Deposit-site selection

Ice retreating from the Durance–Guil confluence into the upper Guil valley (Fig. 1b), while simultaneously operating in a similar fashion in the upper Po valley, led to matching construction of ground, end and lateral moraines in both catchments. In the upper Guil valley, LG ice produced a doublet stillstand at the end of the Allerød, at 2400 and 2500 m asl respectively, and then either melted away or retreated into cirques near the Traversette col and the Lake Lestio area. In the upper Po valley, ice retreat stopped at 2200 m asl and later went through a punctuated withdrawal to 2300 m asl, eventually diminishing toward the Continental Divide and into a couloir on the northeast slope of Mt. Viso. This was followed by rockfall and landslide activity in both catchments, but with mass wasting more prominently present in the upper Po, presumably concurrent with the resurgence of ice in both areas but with ice volumes operating in concert with microclimate favoring disproportional glacier growth depending upon aspect and movement of storm systems. The growth of YD ice resulted in ice advancing out of Lake Lestio (Fig. 2b), overrunning the southern part of the Guil Plateau at the headwaters of the Guil River. A re-advance, presumably the YD, originating below the Col de la Traversette reached the ~ 2450 m asl elevation where it partially buried the inner LG moraine (Fig. 2b). A similar re-advance reached the floor of the upper Po valley overrunning part of the LG surface (~ 2278 m asl) (Fig. 2c) with lateral and ground moraine. Beyond superposition, no C14 is available for age control on the YD re-advances.

Allerød weathering and initial soil genesis on LG surfaces in both catchments was presumably only strong enough to produce A/C/Cu or C/Cu profiles with coarse textures, little organic carbon ($\sim 3\%$) from early successional stage vegetation decay, low (< 10) C/N ratios, early release of soluble elements, with a clay mineral composition largely comprising pre-weathered species. In other words, Allerød soils would have been at best low grade Entisols in the US Taxonomic System or Regosols in the Canada Taxonomic System, similar to young late Neoglacial soils described by Mahaney et al (2016a). Outside the YD moraine limits, soil morphogenesis would have had at best only several centuries head start producing thin, low grade soils. After deposition of YD substrates, hypothetically the same process would have followed suite, and possibly with the advent of warming in the Early Holocene, the Entisol–Regosol soils would have morphed into Inceptisols (Ah/Bw/Cox/Cu profile),

and with the throughput of soil moisture over time leading to oxide–hydroxide production, removable of soluble elements, slow grades of clay mineral genesis in places, and aeolian delivery of pre-weathered minerals in others. What is evident today, is that even with the presence of multifarious lithologies—ophiolites, schist-lustres, mica-schist, serpentine group minerals, talc, gneiss—across the field area, weathering produces Inceptisols, that is, profiles with Ah/Bw/Cox/Cu profiles on all LG and YD surfaces independent of slight changes in slope, ground cover, or anthropogenic activity over the last few millennia. Of perhaps greater significance is that contacts horizon-to-horizon are nearly linear, that is, there are no evident convolutions in any of the 75 sections analyzed. It may be that inordinately thick snow accumulations year-by-year insulate the subsurface so that ice crystal growth and frost heave is at a minimum.

The profiles shown in Fig. 4a, b—sites G3-G3A (Guil N-Fig. 2b) and site V9 (Viso-Fig. 2c) occur with depths of ~38–45 cm, with no more than a ± 10 –15% variance in thickness of the weathered package—Ah/Bw/Cox—of paleosol horizons present at sites across the glaciated landscape. Organic carbon is mostly $\pm 5\%$ and particle size data show minimal clay genesis or incorporation from depositing systems; the former possibly a rapid out-flux of C and N to their respective cycles, the latter quite possibly a result of the lack of mica-rich minerals. Still, with an age-old transhumance activity year-after-year the profiles examined show little-to-nil effect of pounding hooves affecting the upper epipedons of the pedons. It is these Inceptisols (Cryocrepts) that, along with pebble rinds and occasional bedrock outcrops, contain widely distributed evidence of the cosmic airburst centered circa ~13 ka, with at most a 400–500 yr range of soil morphogenesis beforehand. The LG surface had to be in place

to receive the cosmic-pressure–thermal release and the YD would have reworked some of this evidence at a later time, the bulk of which would have been transferable from initial grade pedons to higher grade forms found in place today. Movement of surface clasts within profiles, or between profiles, as a response to the cosmic airburst is unknown.

Ice terminal positions

Ice recession during the late Allerød stopped at various places, offset by ~200–300 m elevation, higher (2500–2400 m asl) in the upper Guil valley, and lower (2200 m asl) in the upper Po catchment. The relative difference in elevation reflects basin dimensions, larger accumulation area in the Guil, somewhat lower in the upper Po, and aspect-west facing in the upper Guil, northeast-east in the upper Po. In both cases, receding ice stopped at breaks in slope with Allerød sediment exposed over a broad plateau in the upper Guil against a narrow catchment in the upper Po valley. The area exposed to the cosmic airburst was ~3 $\times$ larger in the upper Guil compared with the upper Po valley; however, retreat in the Guil was a double stage set of ice stillstands from 2400 to 2500 m, whereas in the upper Po valley, ice recession is recorded as a double moraine arrangement with both sets of deposits nested together and affected by the cosmic event. LG moraines in both catchments have been affected by erosion, such that lateral moraines cannot be used to calculate equilibrium-line altitudes (ELAs), making it possible to use only terminal altitudes to establish relative glacial limits from the LG to the YD. As plotted in Fig. 5, what is clear from this is that the YD reached the inner stillstand elevation of the LG ice ~2450 m in the upper Guil N and S vs. ~2300 m in the upper Po—indicating the glacial mass balances were approximately the same for both the late Allerød and the YD.

Because we do not have well-defined lateral moraines, the establishment of equilibrium-line altitudes (ELAs) is not possible, but intact end moraine (recessional) limits allow estimates of terminal elevations which provide approximate ice limits valley to valley. Calculating YD to LG elevations produces parabolic curves from Guil N and Guil S to the upper Po (Fig. 5). Approximate variations between catchments suggest variable snow accumulations from the Adriatic in the east to the Mediterranean off to the west. These data suggest storm tracks deposited a greater load of snow on the windward west flank vs. the leeward east slope, in tune with normal mass balance differences all along the western and central Alps (Soldati and Marchetti 2017).

Weathering rinds/sand coatings

Weathering rinds and rind thickness have been used for over a half century as relative age indicators for moraines

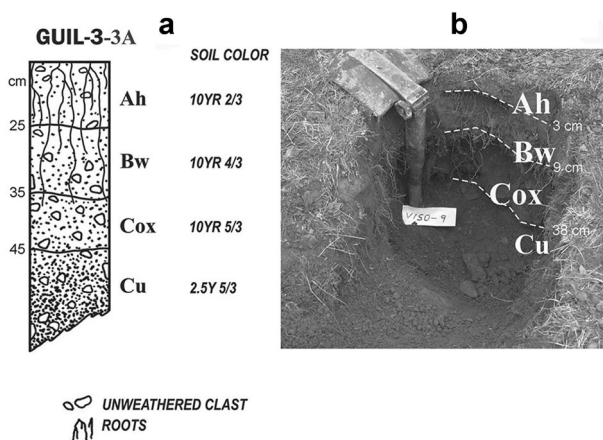


Fig. 4 Representative paleosol sections in the Po valley. **a** Site G3-3A; **b** Site V9 in LG rockfall debris; All LG-YD paleosols analyzed over the last decade carry similar horizon designations and horizon thicknesses within ± 10 –15%. Profile thickness varies from 40 to 60 cm with an average variation of ± 15 cm

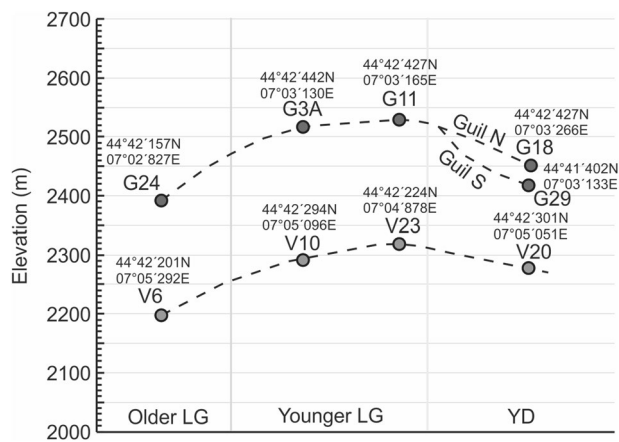
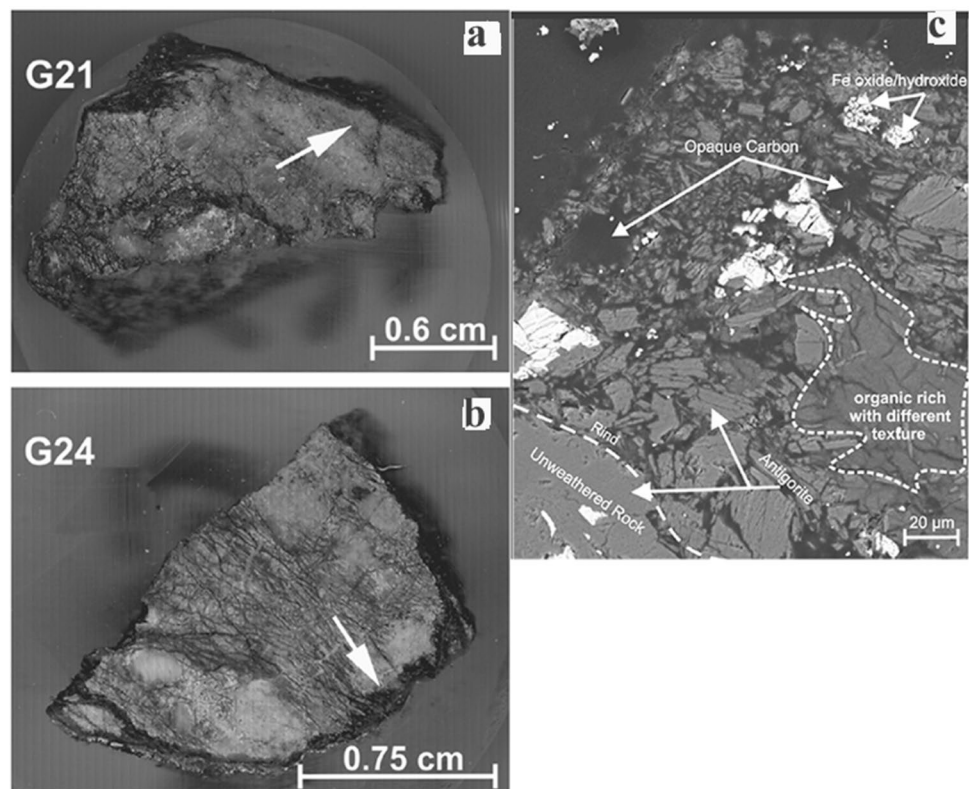


Fig. 5 Diagram illustrating a staggered LG ice retreat in the upper Guil valley relative to the upper Po valley with elevational variations during the LG coupled to elevational differences during the YD in both basins. Approximately a 200-m near-rhythmical elevation difference between the older LG and younger LG mark the Allerød stillstands in all three drainages. Note that the YD terminal moraine elevations vary among all three catchments and in GN and GS it amounts to ~100 m. These data indicate that during the YD, positive glacial mass balances brought glacial terminus positions close to LG elevations

in glacial sequences (Nelson 1954; Sharp 1969; Birkeland 1973; 1999; Ricker et al. 1993; Hall et al. 2001; Sak et al. 2004; Pelt, et al. 2008), on Mars (Mahaney et al. 2012)

and in the Antarctic (Mahaney and Schwarz 2016, 2021), as paleo-weathering/climate change records. Early work showed that rind growth progresses faster than grain loss, so that rind thickness at best yields a minimum relative age. What is important here is that rinds, that is, clasts ensconced in moraines and other landforms tend to lose material to soils and paleosols as they weather from time zero to the present (Dorn et al. 2017). The cosmic event of ~13 ka would have affected both pebble clasts in deposit surfaces and sediment matrices (profiles) with pressure and thermal (P–T) waves leading to clast fracturing, melting and welding of grains, production of Fe and C spherules, and air-quenched micro-features on silt and fine sands. As shown in Fig. 6a, b, rinds in G21 and G24 of LG age (Fig. 2b–G24), yield near continuous rinds with variable thicknesses in the range of 1–3 mm. The rind in G21, rich in secondary Fe, compared with the carbon-rich entity in G24, presents the range of rinds recovered from the field area. Enlarged imagery from site G24 (Fig. 6c) shows details of mechanical fractures in the rind inner surface, reorganization and break up of phalanx-like structures (presumably from P–T stress), along with the production of opaque carbon. These opaque carbon masses, profligate among the rinds analyzed (Mahaney et al. 2013a), must have released material to enclosing soil bodies, the remainder locked into the rind, exposing deep penetration of cosmic forces to the rock core. Hence, as illustrated here, surviving rinds carrying evidence of a cosmic event

Fig. 6 Rind samples. **a** G21 opaque Fe-carbon encrusted rind (arrow); **b** G24 Fe-carbon encrusted rind (arrow); **c** Shattered ~160 µm thick rind with a mix of welded grains (arrows), small masses of opaque carbon and shattered grains



can be expected to embed melted, welded and air-quenched microforms similar to what is present, and variously distributed in soils/paleosols. Examples of cosmic melted/welded and air-quenched sands in Viso paleosols, as in Mahaney and Keiser (2013) and Mahaney et al. (2013a) and in Fig. 4a, b provide examples from site G3A (Guil North, Fig. 2b for location and Fig. 4a for the section). Such melted/welded grains (Fig. 7a), extreme melted-welded microforms (Fig. 7b), and near buckyball features (Fig. 7c), collectively are representative of variably distributed cosmically-affected materials in nearly all profiles examined on the Massif.

Particle size

All the Guil south, Guil north and Viso samples fall within the silty sand to sandy silt brackets (Link 1966), with little differentiation between pedons and parent material. As expected, with a mica-poor lithology, clay content is low measuring below 10% at the maximum and with most pedons registering <5%. As in previous studies, silt registers with a wide range from 15–70%, the highest values in the pedon epipedons (Ah-Bw horizons), which marks what is most likely aeolian-influxed delivery (Smalley 1966) of glacially-ground material sourced from moraines and out-wash fans in the lower valleys. Crossing over to a pedological classification, all samples fall into the sandy loam to silty loam category, none close to the loam zone where clay starts to predominate.

Most unusually, all profiles of LG and YD age fall within the Inceptisol Order of soil classification, the exception being the LIA profiles in the upper Po valley that owing to their young age are difficult to place in the Entisol Order (NSSC 1995). Despite the lack of Ah horizons among this group, and with their very coarse textures, it might be best to classify the C/Cu profiles as weathered–un-weathered beds. All the Inceptisols fall within a thickness of $45\text{ cm} \pm 10\text{--}15\%$, the LIA profiles < 15 cm. The lack of clay movement within the Inceptisols, coupled with little trace of horizon disruption and/or frost heave convolution, tends to follow from the texture assessment. As reported below, the XRD analysis shows a mix of Si:Al 2:1 and 2:1:1 clay minerals, with chlorite often the dominant species.

Soil/Paleosol chemistry

As with the glacial stratigraphy outlined above, paleosols in both LG and YD surfaces yield near equivalent profile depths. Ah horizons show depth variability centered on 10-cm thickness (variance 3–25 cm—see Fig. 4a, b) with colors nearly uniform in the 10YR 2–3 range with organic carbon of 5–8%, fine sediment mixed with clasts in the surface providing copious rind material for analysis. The Bw group of horizons rises to greater thickness of 15–25 cm,

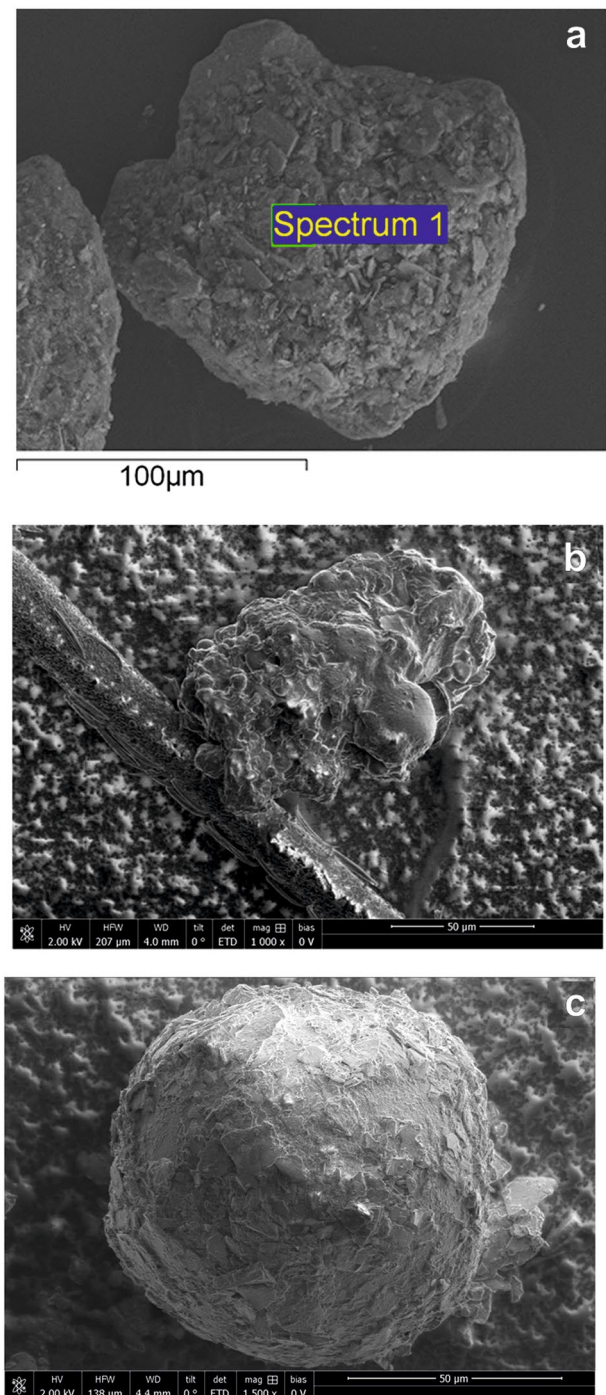


Fig. 7 **a** Indurated welded mixed lithology grains in Site V9-Cox, Upper Po valley; **b** melted-welded fine silts, Site G11-Bw, Guil N (From Mahaney et al., 2016b); **c** Buckyball-like grain with air-quenched micro-features in Site G11-Bw, Guil N (From Mahaney et al., 2016b)

with similar organic carbon amounts but without evidence of organic films on peds. Colors strengthen somewhat to 10YR 4–5 indicating greater hydroxide/oxide release and with little variation across horizons (Cox) downward in

profiles. Despite the low clay content across epipedons in both groups (LG-YD) of paleosols, occasional increases of clay downward amount to only 1%, and never high enough to change the soil classification to the Alfisol group (NSSC 1995). Clast content tends to decrease in the lower horizon groups but no stone counts were taken and root diameter thickness is similar to overlying beds (horizons). The Cox group occupies the greater volume of sediment in most profiles regardless of age but with colors rising with value and reduced chroma falling into the 10YR 5–6 range.

Mineralogy

The XRD data in Fig. 8 (a-Guil S, b-Guil N, and c-Viso) show a mix of 2:1 and 2:1:1 Si:Al layered and interlayered species along with variably distributed talc, serpentine and Na mica. The clay mineralogy (<2 µm) fraction yields near random fluctuations of talc and serpentine, both detrital rather than driven by weathering over time. Within the 2:1

and 2:1:1 clay species, the micas decline upward in some sections but with no clear trend toward vermiculite or any of the vermiculite intergrades, nor is there any neo-formation of illite as one might expect (Bétard et al. 2009). Chlorite also shows an indeterminate tendency toward strong dissolution upward in some sections but without a clear relationship to mica. Hence, there is no evidence of chloritization of mica, and if chlorite is transformed by weathering there may be loss of Si tetrahedrons and/or Al octahedrons to weathering (soil) solutions. The clay minerals recovered from sections in this instance are more related to the various lithologies present than to weathering processes over time.

Geochemistry

Macro-element and microelement databases are in Tables 1, 2, 3 with the rare earth elements (REEs) and Pt elements sorted by catchment in Tables 4, 5, 6. Combined data for macroelement, microelement and REEs/Pt elements in the

Fig. 8 **a** Mineralogy of selected LG-YD-Neoglacial sections in the Lake Lestio area upper Guil South; **b** Mineralogy of selected LG-YD sections in upper Guil north valley; **c** Mineralogy of selected LG-YD-LIA sections in the upper Po valley

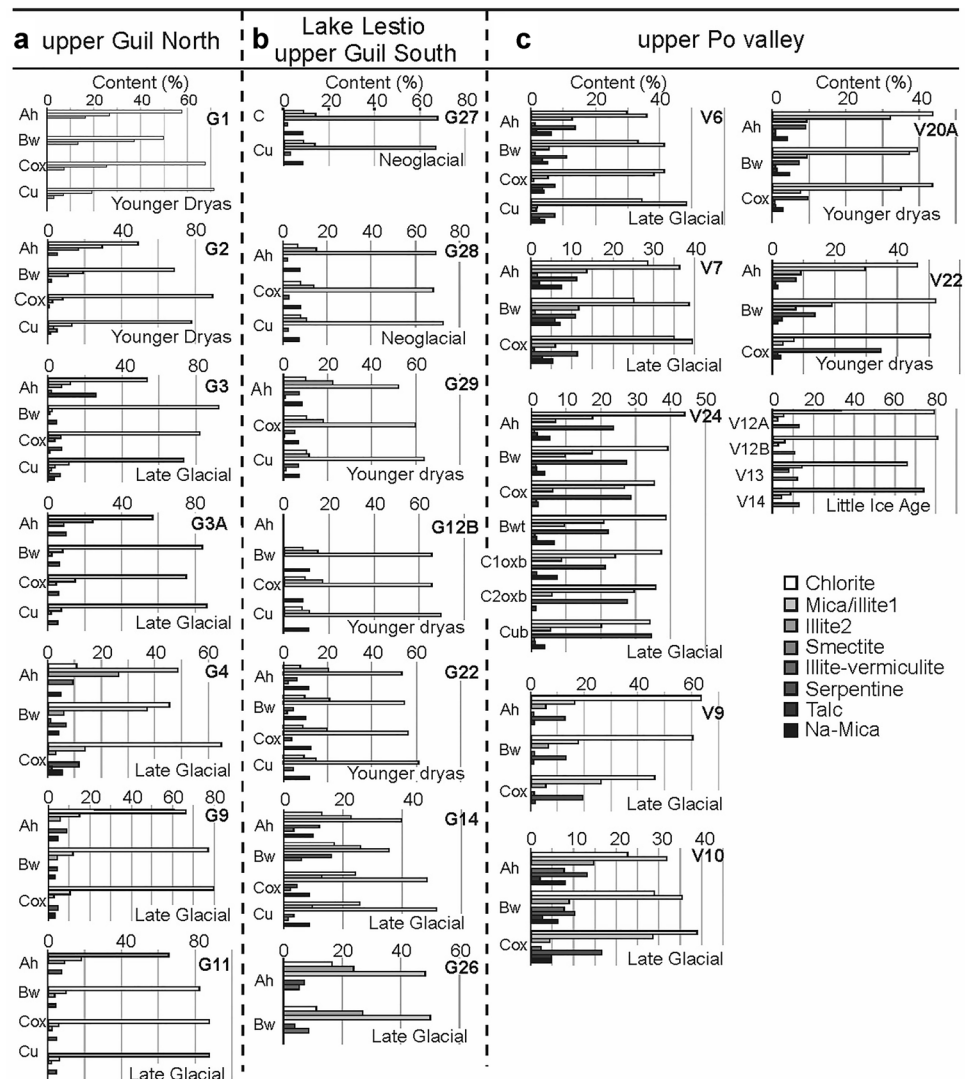


Table 1 Selected macro-, micro- and REE elements in the Lake Lestio Sequence

Site	Horizon	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	CaO %	K ₂ O %	Na ₂ O %	MgO %	CIA (*)	Hf ppm	Sc ppm	Ni ppm	Co ppm	Cr ppm
Crustal	Average	66.6	15.4	5.0	3.6	2.8	3.3	2.5	—	5.3	14	47	17.3	92
Neoglacial														
G27	C1	53.04	19.64	7.07	0.41	3.37	1.73	2.32	78	10	20.1	<20	31.9	150
	Cu	53.68	20.02	7.72	0.53	3.37	1.07	2.30	80	10	22	<20	33.8	150
G28	Ah	53.69	18.85	6.49	0.55	3.25	0.95	2.30	80	10	18.2	190	25.2	140
	Cox	54.12	31.26	7.15	0.62	3.37	0.94	2.37	86	10	19.9	<20	30.5	140
	Cu	52.48	18.85	6.73	0.74	3.25	0.95	2.30	79	10	18.5	310	30.8	140
YD														
G12B	Ah	—	—	—	—	—	—	—	—	—	—	—	—	—
	Bw	51.55	20.02	8.06	1.01	3.49	0.99	2.52	79	10	21.0	220	46.5	170
	Cox	51.76	19.64	7.85	1.94	3.37	1.09	2.59	75	10	19.3	<20	39.1	160
	Cu	47.49	36.45	7.97	3.50	3.37	1.05	2.50	82	<10	19.2	210	46.8	160
G22	Ah	49.62	17.11	7.43	0.11	2.77	0.94	1.69	82	10	18.7	60	17.0	124
	Bw	51.54	18.37	6.99	0.09	3.01	0.86	1.91	79	10	18.9	70	22.0	172
	Cox	53.26	19.83	7.47	0.20	3.37	1.00	2.34	81	10	22.8	120	35.0	186
	Cu	53.69	18.89	8.19	0.40	3.25	1.02	2.30	80	10	22.7	100	37.0	192
G29	Ah	51.76	18.02	5.93	0.36	2.77	0.96	2.11	82	<10	16.5	<20	14.1	140
	Bw	54.54	20.96	6.86	0.31	3.62	1.02	3.44	81	10	20.2	<20	31.2	160
	Cox	53.90	18.19	6.72	0.63	2.77	1.08	2.09	80	10	18.7	<20	15.2	140
LG														
G14	Ah	—	13.92	5.46	2.04	1.86	1.08	2.28	74	4	17.0	79	17	173
	Bw	—	14.33	5.56	2.77	1.55	1.43	2.57	71	4	21.0	64	13	178
	Cox	—	18.37	7.75	1.00	2.21	1.24	3.58	80	3	19.3	174	19	231
	Cu	—	17.78	7.99	1.82	2.14	1.18	3.96	78	4	21.0	345	30	228
G26	Ah	53.90	17.73	6.44	0.39	2.53	0.84	2.73	82	<10	19.0	380	11.2	200
	Bw	54.54	18.13	5.49	0.39	2.77	0.89	2.65	82	10	18.6	<20	8.2	220
	Cox	50.05	19.26	9.20	0.28	3.13	1.16	2.85	81	10	20.6	<20	20.5	290
D														

^aCrustal averages from Rudnick and Gao (2005, Table 11, upper crust); ^b— Insufficient sample. *Chemical index of alteration (CIA) was calculated by molar ratio of $[Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \times 100$, from Nesbitt and Young (1982). The dimensionless number (0–100) indicates relative degrees of weathering (0=low; ~100=high)

pedostratigraphic section V24 are in Table 7. These data, presented below, are discussed later with respect to other sites worldwide.

Guil South catchment

In this cirque (Fig. 2a), two LG, three YD and two Neoglacial sections provide a cross-cut of the valley chemistry providing concentrations of Si, Fe, Al, Ca, K, Na and Mg oxides on the macroelement side and Hf, Sc, Ni, Co and Cr on the microelement side. The bedrock is mainly metabasalt and calcareous schist, with various changes in CaO, especially in G22, the likely result of efficient drainage in the surface of the YD moraine in mid-valley (Fig. 2a). Si/Al ratios show little variation, even within the Neoglacial profiles, all within a 2:1 ratio of Si:Al, which closely fits with the clay mineralogy. Total Fe shows some variation

with increases down-profile in some profiles, e.g., G14 and G26 in the LG group, which might be related to the intense heat of an airburst. Somewhat similar trends exist in G22 and G12B of the YD profiles, decreasing somewhat in the Neoglacial group. The CaO shows minor dissolution in the YD group, disappearing in the LG and Neoglacial sets. The CIA, a chemical index of weathering (Nesbitt and Young 1982) numbered from 1 to 100, the higher number representing stronger weathering and presumably older material (see Goldberg and Humayun 2010, for examples). Throughout the sections analyzed, the CIA indicates little variation with a range of 71–82, with a common value of $80 \pm$. Some profiles show slightly higher values with depth-G14 (LG) and G12B (YD), others show nearly a uniform value with depth. The Neoglacial profiles (G27, G28) that should show lower numbers and less weathering measure within the LG and YD groups, suggesting they consist of reworked weathered

Table 2 Selected chemical elements, Guil Valley North

Site	Horizon	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	CaO %	K ₂ O %	Na ₂ O %	MgO %	CIA	Hf ppm	Sc ppm	Ni ppm	Co ppm	Cr ppm
Crustal average		66.6	15.4	5.0	3.6	2.8	3.3	2.5	(*)	5.3	14	47	17.3	92
YD														
G1	Ah	—	13.70	7.63	5.21	1.06	1.81	4.29	50	4	24.9	89	23	191
	Bw	—	14.64	8.69	6.79	0.81	1.79	5.02	48	3	29.3	103	30	204
	Cox	—	15.12	8.84	8.14	0.73	2.00	5.72	44	3	31.0	114	33	186
	Cu	—	15.02	10.02	9.43	0.77	2.12	7.11	41	2	33.7	135	44	229
G2	Ah	—	13.51	7.85	5.11	1.11	1.50	3.98	51	3	24.1	79	20	173
	Bw	—	13.87	8.89	5.99	0.94	1.74	4.99	48	3	26.9	100	31	210
	Cox	—	14.44	9.59	8.52	0.61	2.00	6.70	43	2	33.2	120	37	230
	Cu	—	14.34	10.34	8.97	0.58	2.10	7.81	41	2	32.8	146	49	258
LG														
G3	Ah	44.07	14.37	8.83	7.21	0.71	1.92	7.23	46	3.2	33.3	163	43	4244
	Bw	45.32	14.10	10.58	9.56	0.37	1.80	8.33	40	2.8	41.3	207	50	374
	Cox	46.65	14.65	10.29	9.28	0.52	2.08	8.22	41	2.8	39.1	241	60	364
	Cu	47.47	15.39	10.22	10.19	0.43	2.34	8.27	40	2.2	36.9	402	63	350
G3A ^a	Ah	46.28	14.66	7.52	5.69	1.01	1.50	5.06	51	4	27.7	<20	25	263
	Bw	49.31	12.74	9.24	8.66	0.65	1.98	6.77	39	2	35.4	<20	37	294
	Cox	50.65	12.49	8.66	8.97	0.69	2.01	6.15	38	3	36.2	<20	41	273
	Cu	48.88	12.51	9.51	10.00	0.58	2.01	7.23	36	3	38.6	<20	46	272
G9	Ah	48.59	14.42	9.08	7.01	0.73	1.69	6.17	47	2	27.3	<20	35	257
	Bw	49.98	16.48	9.92	8.44	0.70	2.02	6.91	46	2	23.2	<20	49	263
	Cox	50.05	15.87	9.54	8.48	0.66	2.00	6.57	45	2	32.6	190	51	267
G11	Ah	47.67	15.12	8.28	7.15	0.67	1.62	5.01	48	3	31.4	<20	28	241
	Bw	50.00	12.83	11.58	7.74	0.67	1.67	5.77	42	4	36.7	<20	40	248
	Cox	50.82	11.88	9.05	8.40	0.66	1.91	6.09	38	3	37.5	<20	43	245
	Cu	50.60	11.96	9.49	9.50	0.52	1.81	6.86	37	3	39.8	<20	46	257
G24	Ah	49.37	15.07	7.84	5.77	1.09	2.04	5.21	63	5	22.9	380	77	279
	Bw	47.43	14.27	10.16	5.78	0.73	1.85	10.10	63	3	23.7	380	22	453
	Cox	48.75	14.57	9.14	5.64	0.79	1.91	12.33	64	3	24.4	940	38	426
	Cu	49.14	14.22	9.10	5.49	0.83	1.97	12.78	63	2	22.8	950	62	559

—Insufficient sample. *Chemical index of alteration (CIA) was calculated by molar ratio of $[\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100$, from Nesbitt and Young (1982). The dimensionless number (0–100) indicates relative degrees of weathering. ^aSites G3 and G3A are 3 m apart

sediment. The data in Table 1 show on average higher weathering values in Guil S compared with the databases in Guil N (Fig. 2b; Table 2) and the Viso group (Fig. 2c; Table 3). Microelements, such as Ni, Co and Cr, possible indicators of cosmic airbursts, yield elevated concentrations in some instances—Ni, as in G26-Ah, G14-Cu and G28-Cu—but without elevated Fe, Co and Cr. The Hf/Sc ratio that may show variations relative to bedrock are remarkably uniform across the sequence.

The REEs and Pt tell conflicting stories (Table 4) in support of an airburst in Guil S (Fig. 2a). Within the LG, the full range of REEs in G26 meets above crustal averages for nearly every element, only Tb below. For site

G14, only Ce and Nd register one horizon above average, with Tb, Lu and Th showing slightly higher concentrations in variable horizons. Pt yields a different story with higher than average crustal concentrations in G14 compared with G26. In fact, the Pt/Pd ratios in G14 are 10 to 23 times the crustal values and Ir is several orders of magnitude higher than the crustal average, values at ~40+ throughout the section. Site G26 was not analyzed for Ir because the Pt/Pd ratios were below the crustal average. Within the YD-Neoglacial group, only G29 (YD) was analyzed, and across the board, all REEs were in staggered order near or above crustal average.

Table 3 Selected macro-, micro- and REE elements in the Viso sequence, upper Po River

Site	Horizon	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	CaO %	K ₂ O %	Na ₂ O %	MgO %	CIA (*)	Hf ppm	Sc ppm	Ni ppm	Co ppm	Cr Ppm
Crustal	Average	66.6	15.4	5.0	3.6	2.8	3.3	2.5	(*)	5.3	14	47	17.3	92
LIA														
V12A		–	16.04	9.45	9.42	0.55	2.67	7.06	42	2	31.5	<1	42	256
V12B		–	15.93	9.94	9.43	0.54	2.80	6.98	42	2	32.5	<1	47	237
V13		–	15.29	11.28	8.40	0.80	2.16	7.30	44	3	34.4	<1	53	279
V14		–	15.44	10.79	9.33	0.54	2.17	7.76	42	3	34.4	<1	55	261
V8	Ah	–	7.69	36	86	1.29	1.34	2.93	56	3	25.6	<1	8.6	<50
	C	–	8.20	30	70	1.83	1.45	3.16	55	3	2.80	<1	<0.5	<50
	Cu	–	8.15	47	77	1.78	1.44	4.05	52	3	29.8	<1	<0.5	<50
YD														
V20 ^a	Ah	48.38	15.40	7.55	3.98	1.81	1.0	4.89	59	2.7	25.2	<20	36	233
	Bw	48.70	17.18	8.92	4.14	1.94	1.10	6.00	60	2.6	27.4	290	42	258
	Cox	49.53	17.29	9.40	4.55	2.02	1.11	6.57	58	2.6	25.1	570	42	311
V20A ^a	Ah	50.54	15.69	8.36	3.90	1.85	1.40	4.87	58	2.7	21.7	137	26	233
	Bw	52.03	17.51	9.20	4.30	1.99	1.57	5.97	58	2.6	23.2	169	36	271
	Cox	52.09	17.25	9.23	4.48	2.03	1.54	6.26	57	2.6	24.4	183	41	278
V22	Ah	47.45	14.27	7.39	3.77	1.60	1.16	5.46	58	2.6	19.8	171	28	241
	Bw	47.97	14.93	8.63	4.91	1.50	1.44	7.01	54	3.0	23.7	211	38	304
	Cox	47.22	13.81	9.75	7.14	0.71	1.77	9.78	45	1.8	26.3	322	48	454
V23	Ah	47.90	15.09	7.62	3.55	1.86	1.37	4.12	69	3.9	24.7	1.29	30	349
	Bw	50.41	16.30	9.74	3.07	2.23	1.16	5.60	72	3.4	25.1	1.97	34	475
	Cox	49.47	15.34	9.95	4.40	1.60	1.65	7.53	67	3.0	25.5	2.76	46	586
LG														
V6	Ah	47.79	15.13	7.86	2.32	1.85	1.20	4.71	73.8	3	17.9	<20	20	253
	Bw	52.77	17.30	9.08	2.95	1.79	1.75	6.97	72.7	2	22.4	470	41	327
	Cox	53.21	17.39	9.02	3.53	1.67	1.88	7.21	71.1	3	24.7	300	44	347
	Cu	53.92	17.23	8.96	3.09	1.92	1.77	7.35	71.8	3	27.1	440	46	349
V7	Ah	49.27	14.63	7.99	3.17	1.69	1.43	5.09	69.9	3	19.0	290	22	244
	Bw	51.71	17.02	9.50	3.46	1.82	1.69	6.54	70.9	3	22.6	760	40	317
	Cox	53.60	17.20	9.03	3.37	1.82	1.84	6.46	71.4	2	22.9	560	40	318
V9	Ah	45.81	15.57	8.66	5.66	1.29	1.65	5.99	52	2.3	22.6	177	33	261
	Bw	45.86	15.60	8.93	5.54	1.25	1.55	6.64	53	2.3	24.0	201	41	287
	Cox	46.57	15.92	9.41	6.18	1.19	1.63	7.53	51	2.3	25.7	239	46	312
V10	Ah	44.05	14.09	8.04	4.46	1.60	1.56	5.75	53	2.6	21.6	201	29	352
	Bw	46.78	14.70	9.95	5.75	1.05	1.69	7.61	76	2.8	23.6	288	38	393
	Cox	51.34	14.68	8.76	6.44	0.96	2.04	7.59	76	1.8	23.6	281	38	364

– Insufficient Sample

Chemical index of alteration (CIA) was calculated by molar ratio of $[\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100$, from Nesbitt and Young (1982). The dimensionless number (0–100) indicates relative degrees of weathering. ^aNested V20–V20A 1 m apart

Guil North catchment

Across the LG and YD sections (Fig. 2b) in the macro-element group it is the Fe and CIA that stand out in Table 2. The Fe ranges from 7.5 to 11.6%, the highest values coming in G3, G11 and G24. These values may represent heating during an airburst which surely must be multi-directional, fully affecting nearly the whole

G3–G3A profiles, split between various horizons, i.e., the Bw in both G11 and G24. The parent material (Cu horizons) in G1 and G2, of YD age, are elevated as well suggesting sediment reworking. Across the macro-element group, Ca and Na, the most mobile elements, show dissolution in the upper horizons (the epipedons–Ah + Bw horizons) following acidic buildup in the Ah group. Compared with Guil S, the CIA is lower by half, possibly from

Table 4 REE concentrations^{ab} and Pt/Pd ratios in the Lake Lestio Sequence

Site	Horizon	La ppm	Ce ppm	Nd ppm	Sm ppm	Eu ppm	Tb ppm	Yb ppm	Lu ppm	Th ppm	Pt ppb	Pd ppb	Pt/Pd	Ir ppb
Crustal	Average	31	63	27	4.7	1.0	0.7	1.96	0.31	10.5	0.5	0.5	1.0	0.02
Neoglacial														
G27	C1	47.8	98	44	7.7	1.7	<0.5	3.7	0.6	18.7	–	–	–	–
	Cu	54.5	114	35	8.9	1.8	<0.5	4.0	0.2	19.7	–	–	–	–
G28	Ah	44.7	102	43	7.2	1.5	<0.5	3.5	0.5	17.4	–	–	–	–
	Cox	50.7	95	44	8.2	1.5	0.7	3.6	0.2	16.4	–	–	–	–
G12B	Cu	46.1	102	45	7.1	1.8	<0.5	3.3	0.6	17.8	–	–	–	–
	Ah	–	–	–	–	–	–	–	–	–	–	–	–	–
G22	Bw	58.4	115	40	8.7	2.2	1.1	3.5	0.6	18.5	–	–	–	–
	Cox	58.1	119	57	8.5	1.8	1.8	3.2	0.5	19.0	–	–	–	–
	Cu	59.5	126	71	8.7	2.4	0.9	2.6	0.5	18.4	–	–	–	–
	Ah	35.0	69	25	5.1	0.8	<0.5	2.1	0.1	12.9	–	–	–	–
G29	Bw	37.8	88	35	5.5	1.2	<0.5	2.5	0.4	16.3	–	–	–	–
	Cox	64.0	123	76	11.2	2.8	1.9	5.9	1.0	20.0	–	–	–	–
	Cu	57.9	112	48	9.7	2.2	<0.5	4.8	0.8	19.9	–	–	–	–
	Ah	36.8	82	27	5.5	1.5	<0.5	2.5	0.4	14.4	0.5	1.8	0.3	–
G29	Bw	52.9	113	57	8.7	1.6	1.0	3.3	0.2	18.7	1.0	3.3	0.3	–
	Cox	42.9	92	33	6.2	1.2	<0.5	3.2	0.1	17.4	0.7	2.2	0.3	–
LG														
G14	Ah	4.6	43	<5	<0.01	<0.5	2.3	0.17	0.94	6.7	17	1.7	10	1.0
	Bw	3.5	52	23	<0.01	<0.5	2.6	0.26	1.10	5.3	8	<0.5	16	0.9
	Cox	6.1	59	15	<0.01	<0.5	2.4	<0.05	1.34	11.6	10	0.7	14	1.6
	Cu	6.8	76	30	<0.01	<0.5	3.4	0.28	1.51	10.0	35	1.5	23	1.5
G26	Ah	36.9	79	22	4.9	1.0	<0.5	2.0	0.1	14.6	0.7	1.7	0.4	–
	Bw	45.3	95	43	6.2	1.2	<0.5	2.4	0.3	13.4	0.5	1.2	0.4	–
	Cox	44.5	96	30	6.4	1.8	<0.5	3.3	0.5	15.6	0.6	1.1	0.5	–
	D	44.5+												

^aCrustal abundance from Rudnick and Gao (2005, Table 11); ^b– Insufficient sample

lower Al and imbalances across the Ca–Na–K–Mg group. CIA is nearly uniform between the LG and YD, only G24 somewhat higher and averaging in the 63–64 range, possibly a reflection of plant variations, as all other environmental parameters (macroclimate-aspect-slope) are similar to the other sites. The primary bedrock is schist-luster, metamorphosed marl.

Within the REEs (Table 5) in the LG samples, only Tb and Yb show slight elevations above average crustal concentrations. The Pt group on the whole is 1–3 × the average ratio, with G11-Bw registering a value of 26. Iridium follows Pt with values above an order of magnitude relative to average concentrations in G3A, G9 and G11. Across the YD, most elements register below crustal average, the Pt/Pd close to crustal average, only the G2-Cu horizon (representative of un-weathered moraine sediment), rising to x ~ 10 the average.

Viso group

The Viso group (Fig. 2c; Table 3) shifts to a mix of amphibolitic schist, gabbro and serpentine, with yields of Si similar to sites in Guil N and S, but with Al more aligned with Guil N than Guil S. The Si:Al ratios for most sites register 2:1, and in some cases Si increases down-profile indicating active hydrolysis in the surface. As in the other sections of Guil S and N, some buildup of Fe occurs in sections of both the LG and YD profiles. This may highlight stronger oxidation with depth, although there may be dilution effects in the Ah horizons. As in the other sections of Guil S and N, increasing concentrations of Ca and Na, two of the most mobile cations, tend to increase with depth in most profiles. Mg, and to some degree K, follow the same pattern, except that K's distribution is less uniform. The CIA ranges from 50 to 70 overall across the LG and YD, with the Neoglacial

Table 5 REEs, Th, Pt, Pd, Ir, and Pt/Pd ratios in cosmically-impacted Late Glacial and YD paleosols, Guil River catchment, Western Alps

Site	Horizon	La ppm	Ce ppm	Nd ppm	Sm ppm	Eu ppm	Tb ppm	Yb ppm	Lu ppm	Th ppm	Pt ppb	Pd ppb	Pt/Pd	Ir ppb
Crustal	Average	31	63	27	4.7	1.0	0.7	1.96	0.31 ^a	10.5	0.5	0.5	1.0	0.02
YD	Group													
G1	Ah	15.1	34.0	31.0	3.4	1.2	<0.5	2.5	0.21	3.5	–	–	–	–
	Bw	16.4	28.0	23.0	3.9	0.9	<0.5	2.6	0.30	4.1	0.9	0.8	1.1	–
	Cox	11.0	23.0	13.0	3.5	1.1	<0.5	2.8	0.28	2.1	0.6	<0.5	1.2	–
	Cu	7.8	23.0	11.0	3.2	1.3	<0.5	3.1	0.28	1.3	1.7	1.0	1.7	–
G2	Ah	12.0	29.0	12.0	3.2	0.8	<0.5	2.3	0.22	2.8	–	–	–	–
	Bw	5.5	18.0	8.0	2.8	0.9	<0.5	2.5	0.22	0.9	–	–	–	–
	Cox	5.7	14.0	10.0	3.0	0.8	0.7	2.5	0.23	1.1	1.1	<0.5	2.2	–
	Cu	3.9	17.0	8.0	2.7	0.8	<0.5	2.5	0.22	0.3	5.4	0.5	10.8	–
Late Glacial	Ah	14.1	36.0	26.0	4.9	2.2	1.9	2.3	0.11	3.5	1.3	1.3	1.0	–
G3	Bw	9.9	26.0	18.0	5.0	2.1	0.5	2.5	0.10	2.3	2.2	0.6	3.7	–
	Cox	7.7	25.0	19.0	4.6	1.8	0.5	2.5	0.11	1.1	1.2	0.6	2.0	–
	Cu	5.4	23.0	9.0	4.4	1.9	1.3	2.5	0.12	<0.5	–	–	–	–
	Cu	5.4	23.0	9.0	4.4	1.9	1.3	2.5	0.12	<0.5	–	–	–	–
G3A ^a	Ah	15.6	35.0	<5	3.4	1.0	<0.5	2.2	0.39	3.9	2.1	0.9	2.3	4.0
	Bw	9.1	28.0	15.0	3.8	1.0	<0.5	2.8	0.43	1.6	<0.5	0.7	0.7	2.0
	Cox	9.9	31.0	8.0	4.0	0.9	<0.5	3.1	0.43	2.5	<0.5	0.5	1.0	3.0
	Cu	8.0	27.0	10.0	4.0	1.2	<0.5	3.1	0.54	1.5	<0.5	<0.5	1.0	3.0
G9	Ah	10.8	22.0	12.0	3.2	1.2	<0.5	2.4	0.26	2.9	2.2	0.7	3.1	–
	Bw	9.2	22.0	14.0	3.6	1.0	1.2	3.2	0.33	1.6	2.4	0.7	3.4	–
	Cox	8.1	20.0	12.0	3.6	1.6	0.9	3.3	0.33	1.3	1.4	0.7	2.0	–
	Cu	5.7	23.0	9.0	3.9	1.3	0.7	3.3	0.47	1.0	<0.5	<0.5	1.0	3.0
G11	Ah	13.6	31.0	16.0	4.0	1.0	<0.5	2.5	0.51	4.3	<0.5	0.6	0.8	4.0
	Bw	12.4	32.0	8.0	4.3	1.1	<0.5	3.4	0.49	2.4	15.6	0.6	26	3.0
	Cox	8.8	20.0	12.0	3.9	1.1	0.7	3.1	0.43	1.6	<0.5	0.6	0.8	3.0
	Cu	5.7	23.0	9.0	3.9	1.3	0.7	3.3	0.47	1.0	<0.5	<0.5	1.0	3.0
G24	Ah	17.7	41.0	21.0	3.5	0.9	<0.5	2.6	0.30	5.5	0.8	0.7	1.1	1.0
	Bw	11.2	32.0	14.0	3.1	0.9	<0.5	2.4	0.20	2.7	1.4	1.1	1.3	0.9
	Cox	9.4	29.0	10.0	3.1	0.7	0.8	2.2	<.05	3.3	2.1	1.6	1.3	1.6
	Cu	7.9	25.0	7.0	1.5	0.6	<0.5	2.2	0.20	3.5	2.3	1.8	1.3	1.5

(–)=No detection. ^aSite G3A is located juxtaposed with site G3 in the inner LG moraine

samples producing somewhat lower values and an overall lower grade of weathering, a distinct difference from the Neoglacial profiles in Guil S.

Within the LG (Table 6), all four sites register staggered concentrations, about half the samples inconsistently slightly above the average crustal benchmark. Again Pt/Pd is only available for V10 and then with values just below an average of 2.0, whereas Ir ranges upward from 3.0 ppb, that is 45× the crustal average. This is the site with the very high soot content. Again, within the YD and LIA, sample concentrations are below crustal average in most cases. Pt/Pd ratios show contrasting results with averages of near ~1.0 for the YD, rising considerably within the LIA samples where concentrations in V12A and V12B reach to 57× crust. Moving on with Ir, values rise to 75× crust in V13. These LIA sites, sourced high up (~2450 m asl) in the couloir on the

northeast side of Mt. Viso, have received sediment from the arete (3150 m asl) marking the continental divide, prime locations to receive direct P/T from the proposed airburst.

The pedostratigraphic complex in the lower Po valley at ~2000 m asl (Fig. 1), comprises a doublet section that appeared to be YD over LG outwash when collected. The samples yield a weathering chemistry that places both the upper and lower deposits equivalent in age, and likely all LG. As shown in Table 7, the CIA places both paleosols of similar age, at odds with the field assessment. Admittedly, total Fe is slightly higher in the lower pedon, about 0.5%, which might provide a basis for advanced age in the lower unit, but without extractions for dithionite-Fe, it is difficult to substantiate relative age on total Fe extraction values alone. As well the refractory oxides show little variance

Table 6 REEs and Pt/Pd concentrations^a in the Viso LIA-LG Chronosequence

Site	Horizon	La Ppm	Ce ppm	Nd ppm	Sm ppm	Eu ppm	Tb ppm	Yb ppm	Lu ppm	Th ppm	Pt ppb	Pd ppb	Pt/Pd ppb	Ir ppb
Crustal	Average ^b	31	63	27	4.7	1.0	0.7	1.96	0.31	10.5	0.5	0.5	1.0	0.02
LIA														
V12A	–	3.3	14	18	3.5	0.9	<0.5	3.2	0.26	<0.2	4.9	<0.5	9.8	0.9
V12B	–	3.0	10	11	3.5	1.0	<0.5	3.6	0.19	<0.2	0.7	<0.50	1.4	1.0
V13	–	7.5	21	<5	4.4	1.5	<5	4.7	0.32	1.6	45.7	0.8	57.1	1.5
V14	–	4.5	20	<5	4.0	1.0	<0.5	4.4	0.21	<0.2	0.7	0.6	1.2	1.0
V8	Ah	18.7	40	21	4.9	1.0	<0.5	3.4	0.22	6.8	13	2.0	6.5	1.3
	C	15.8	47	<5	4.9	1.3	<0.5	3.6	0.24	3.9	–	–	–	0.9
	Cu	12.0	30	19	4.6	0.9	<0.5	3.5	0.34	3.3	–	–	–	–
YD														
V20	Ah	23.5	46	21	4.1	1.0	0.6	2.1	0.28	6.2	2.1	2.4	0.9	–
	Bw	21.3	46	28	3.8	1.0	<0.5	2.1	0.25	5.5	1.6	1.4	1.1	–
	Cox	21.4	45	28	4.0	1.1	0.8	2.2	0.35	5.6	1.8	1.2	1.5	–
V20A	Ah	25.0	42	18	3.9	0.9	<0.5	2.3	0.24	5.5	1.9	1.0	1.9	–
	Bw	23.3	45	30	3.8	0.8	<0.5	2.4	0.31	5.4	1.1	1.2	0.9	–
	Cox	22.6	50	17	4.0	1.0	<0.5	2.3	0.35	6.2	0.9	1.2	0.8	–
V22	Ah	24.6	44	23	3.8	0.9	<0.5	2.4	0.27	5.4	1.4	1.5	0.9	–
	Bw	20.5	43	15	3.5	0.9	1.1	2.0	0.30	4.8	5.6	4.7	1.2	–
	Cox	11.4	26	18	3.3	1.0	0.6	2.9	0.31	3.0	830	1110	0.7	–
V23	Ah	22.2	42	22	4.5	1.0	0.8	2.4	0.27	4.6	0.9	0.8	1.1	–
	Bw	23.7	47	26	5.0	1.1	1.4	2.6	0.36	5.1	1.1	1.1	1.0	–
	Cox	20.8	45	20	5.2	1.4	<0.5	2.9	0.33	5.2	1.3	1.3	1.0	–
Late Glacial														
V6	Ah	24.4	44	14	3.9	1.1	<0.5	2.3	0.35	5.6	2.0	0.9	2.2	–
	Bw	28.5	75	29	5.4	1.3	2.2	2.5	0.41	8.3	2.0	1.0	2.0	–
	Cox	30.7	74	29	5.5	1.5	<0.5	2.7	0.39	9.0	2.1	1.1	1.9	–
	Cu	35.1	73	42	6.1	1.5	<0.5	3.4	0.41	9.2	2.7	1.3	2.1	–
V7	Ah	20.7	47	20	3.7	1.2	0.8	2.3	0.26	4.9	1.7	0.8	2.1	–
	Bw	24.6	64	28	4.8	1.7	<0.5	2.5	0.33	6.6	4.3	1.1	3.9	–
	Cox	28.1	77	39	5.6	1.4	<0.5	3.2	0.43	7.7	4.2	1.2	3.5	–
V9	Ah	12	82	14	3.2	0.7	<0.5	2.6	0.35	2.8	3.5	5.4	0.7	–
	Bw	13.8	31	16	3.5	1.1	0.9	2.4	0.26	3.6	1.4	1.1	1.3	–
	Cox	11.7	24	12	3.4	0.9	0.6	3.0	0.33	3.2	7.2	0.9	8.0	–
V10	Ah	21.2	48	17	3.8	1.2	<0.5	1.7	0.37	5.3	1.3	1.6	0.8	4.0
	Bw	21.7	48	18	4.2	1.1	<0.5	2.2	0.38	5.2	1.4	0.7	2.0	4.0
	Cox	19.1	50	18	4.7	1.5	<0.5	2.2	0.37	7.7	1.0	0.9	1.1	3.0

^aCrustal average from Rudnick and Gao (2005). –No detection

in age. The Si:Al ratios are similar to all other sites. Hf/Sc ratios indicate similar lithologies top to bottom of the section. Ni/Fe ratios show no evidence of cosmic airburst and there are no elevated concentrations of Co and Cr. The REEs follow along with a similar distribution as found in the upper Po valley above 2200 m elevation. The Pt/Pd ratios throughout the pedostratigraphic column are less informative with values normal to the crust with most values < 1. The samples were not analyzed for Ir because the Pt counts were low.

Discussion

Glacial stratigraphy-YDB

As glacial recession progressed, ice retreated up the Guil valley toward Mt. Viso (Fig. 1), the main valley glacier dividing into separate ice streams, one retreating into the Col de la Traversette cirque to the north (Fig. 2b), the other retreating toward an unnamed cirque near Lac Lestio (2510 m; Fig. 2a) located below the western summit of Mt. Viso (Fig. 1b). The total retreat distance from Sisteron in the

Table 7 Selected macro-, micro- and REE elements in the Viso 24 section, upper Po valley

Site	Horizon	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	CaO %	K ₂ O %	Na ₂ O %	MgO %	CIA*	Hf ppm	Sc ppm	Ni ppm	Co ppm	Cr ppm
Crustal	Average									5.3	14	47	17	92
V24	Ah	44.01	13.47	8.03	4.94	0.95	1.51	6.98	65	2.2	21.5	239	33	365
	Bw	48.25	15.06	9.20	6.07	1.09	1.74	7.73	67	2.5	24.8	248	37	383
	Cox	50.48	16.38	9.27	5.52	1.45	1.71	6.77	65	2.2	24.2	226	33	333
	Bwb	47.96	16.30	9.83	6.50	1.22	1.79	6.89	63	2.2	26.8	212	43	343
	Coxb1	48.16	16.23	9.80	6.40	1.21	1.77	6.68	63	2.5	26.2	240	44	337
	Coxb2	51.19	16.84	9.78	6.20	1.50	1.87	6.46	64	2.8	25.4	212	36	298
	Cub	48.91	15.13	9.56	6.40	1.23	1.73	8.14	62	2.5	26.2	326	44	432
		La ppm	Ce ppm	Nd ppm	Sm ppm	Eu ppm	Tb ppm	Yb ppm		Lu ppm	Th ppm	Pt ppb	Pd ppb	Pt/Pd
Crustal	Average	31	63	27	4.7	1.0	0.7	1.96	–	0.31	10.5	0.5	0.5	1.0
	Ah	14.1	29	26	3.0	0.9	<0.5	2.2	–	0.26	3.4	1.5	1.8	0.8
	Bw	15.7	35	22	3.4	1.1	<0.5	2.3	–	0.29	3.5	1.3	1.6	0.8
	Cox	19.6	44	20	4.0	1.1	<0.5	2.1	–	0.30	4.7	1.0	1.2	0.8
	Bwb	18.1	38	17	3.9	1.1	<0.5	2.5	–	0.22	4.1	1.3	1.3	1.0
	Coxb1	18.2	40	23	4.0	1.1	<0.5	3.0	–	0.28	4.5	1.8	2.2	0.8
	Coxb2	22.5	52	30	4.6	1.3	<0.5	2.4	–	0.34	5.4	1.2	1.6	0.7
	Cub	19.2	48	19	4.4	1.3	<0.5	2.8	–	0.34	4.8	1.6	1.8	0.9

*Chemical index of alteration (CIA) was calculated by molar ratio of $[\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100$, from Nesbitt and Young (1982). The dimensionless number (0–100) indicates relative degrees of weathering. –Not applicable

lower Durance Valley to the moraines near the Refuge du Viso in the upper Guil is approximately ~105 km. The Po Glacier retreated directly from the Po canyon mouth to the moraine belt at ~2200 m, a distance estimated at ~35 km into a wide amphitheater to the NE of Mt. Viso (Fig. 2c), with one segment of the valley system confined onto a prominent couloir (Fig. 3b) extending to the south up onto the flanks of Mt. Viso itself. In both catchments, glacial retreat during the Bølling-Allerød interstadial exposed coarse clastic deposits and much of the valley and surrounding area, to warm/humid conditions (Thiagarajan et al. 2014).

Continued ice retreat exposed the valley and surrounding area to increased warm/humid conditions, fostering plant growth, and initial soil development. This was followed by instantaneous conflagration, of sufficient intensity to carbonize and volatilize all or most tundra vegetation, and initial soil sediment, at the postulated airburst—the YDB (12.8 ka). Thus, these fired mid-LG stillstand recessional moraines provided resident host material for weathering and soil development (Mahaney et al. 2013a), with deposits still containing residual evidence of the cosmic event. With the onset of cooler conditions during the YD and reversal of the negative glacial mass balance in the upper valleys, the situation reversed causing a glacial advance and production of a push moraine complex at ~2450 m, with 90% of 100 cobble/pebble grade clasts measured at 270° azimuth, due west or down valley.

Soils present in LG sediment at time of the airburst are projected to have been thin immature profiles with Ah/C/Cu and/or C/Cu (variant A or Ah/Cu) horizonation similar to nearby profiles described by Mahaney et al. (2016a) with very low organic carbon (<5%). The LG successional stage vegetation present at the time of the airburst is considered the prime source for C-rich spherules observed in weathering rinds (Mahaney and Keiser 2013; Mahaney et al. 2013a) and on sand/silt grains present in paleosols (Fig. 4a, b). As the Allerød climate warmed, the early successional stage alpine grassland of the (mid-Late Glacial) was probably wet tundra, and as the high-temperature cosmic airburst (YDB) descended upon the study area, we hypothesize most life was likely destroyed. Coupled with carbon and other materials either volatilized, charred, or left as carbon Fe spherules, welded/encrusted microforms resided in soils (now paleosols), and/or as opaque carbon in weathering rinds. Soot contents in these paleosols, although variable, provide the highest counts measured anywhere in Europe (see site V10, upper Po Valley). Variable local rock species were melted, reformed, and welded into multifarious forms as described below and in Fig. 7a–c.

If enough carbon existed in successional stage vegetation and in first generation soils at the time of the YDB-black mat, it is probably preserved in the present opaque carbon spherules and fossil necklace carbon spherule forms variably distributed in Ah/Bw/Cox horizons of the G3-11 and

G4 paleosols in the upper Guil Valley. A limitation to this postulate is that at the onset of the YD climate episode, if the surfaces of the LG moraines were covered with an early successional stage alpine grassland that was probably wet tundra in early developing stages (Mahaney and Keiser 2013), vegetation that was centuries old, at most, vegetal carbon would have been a minimum necessitating the import of carbon from adjoining areas. Thus, the organic carbon content in the Late Allerød soils at the time of the airburst was probably similar to what exists in soils at sites G8 and G10, as reported by Mahaney et al. (2016a). Postulating further that the high-temperature cosmic airburst descended upon the area, and with all or most life likely destroyed, some species in various niches were possibly genetically modified, over a wide but indeterminate area. Thus, the main question of equating the cosmic evidence designated here, with the established cosmic-black mat YDB age, relies on the postulated sedimentation link of mid- to late Allerød ~ 12.5–13 ka vegetation and sediment locked up in the airburst sediment of the YDB. Therefore, bringing airburst sediment and its various lines of SEM micro-features and chemical composition evidence allied to isochronous C14 ages for the black mat cosmic event locks it up with external events worldwide (i.e., the YDB). Taking the proposed YDB airburst a step further, it is important to note that when the last glaciation came to an end, ice retreat up both the Guil and Po valleys locked in Allerød-age deposits above 2400 m in the Guil valley and 2200 m in the upper Po valley.

Nested recessional stillstand moraines of the late-LG at ~ 2400 m asl, located in the upper Guil Valley, approximately 1 km from the drainage divide at ~ 3000 m asl (Col de la Traversette, Fig. 1), overrun by a re-advance of ice, presumed of YD age (sites G1 and G2, Figs. 1b; 2b) (Mahaney et al. 2016a), provide a stratigraphic succession of YD/LG deposits. Because weathering-rind histories, and hence, paleosols in clastic debris of these mid-LG and YD deposits are similar in many properties, depth in particular for the pedons, they are considered to have ages separated by centuries or possibly up to just over a millennium, at best. Whether mid-LG ice remained in the Traversette cirque or disappeared prior to the YD is unknown, but from the superposed record in the upper Guil, it is certain that YD ice re-advanced to ~ 2450 m asl, overrunning any pre-existing mid-LG recessional moraines to occupy a stillstand position for an indeterminate amount of time. Because the YD is the latest climatic cooling event during the insolation warming trend of the LG record (Ralska-Jasiewiczowa et al. 2001; Gibbard 2004; Mahaney et al. 2008), moraines emplaced during the event need to be studied for composition compared with earlier LG deposits. While composition of moraine deposits is not expected to yield significant information, clast fabric might yield information related to thrusting effects and the presence of cosmic grains, elevated

REEs and fired rinds might yield new information on sediment reworking.

Black mat-the catastrophic controversy

The YDB airburst event, hypothesized to have triggered the YD cooling episode at ~ 12.8 ka, followed from the end of a warming trend that started ~ 14.7 ka (Vanderhammen and Hooghiemstra 1995; Van der Hammen and Van Geel 2008; Teller et al. 2002; Lowe et al. 2008), and perhaps earlier (Thiagarajan et al. 2014), as suggested by Warner (2012). Evidence for the cosmic airburst event, established by Wittke et al. (2013), hypothesized to have generated the YD climatic reversal, is vigorously debated in the literature (Firestone et al. 2007; Kennett et al. 2007, 2009, 2015; Holliday et al. 2014; Haynes 2008; Ge et al. 2009; Mahaney and Keiser 2013). Critical reviews of the YDB event espoused by Vanderhammen and Van Geel (2008) argue that wildfires at the YD onset do not require an airburst, and similarly, Broecker et al. (2010) argued that YD climate change does not require an airburst, as it could be the result of lightning strikes. However, neither group has presented evidence in refutation of an airburst. Meltzer et al. (2014) argue that most ¹⁴C dates documenting the YDB are not isochronous, but this has been refuted using Bayesian statistics by Kennett et al. (2015), who proved that widespread YDB layers on several continents are coeval within the dating uncertainties of one standard deviation. Other critics have argued that the YDB airburst event by itself could not generate a glacial advance lasting over 1 kyr, but this argument may be discounted (Lowe et al. 2008; Teller et al. 2002) because of feedback loops in the thermohaline circulation systems, i.e., once circulation ceased in the North Atlantic, systemic inertia caused a delay of ~ 1400 years before normal circulation resumed. In the mountains, high altitude circulation and microclimate conditions may have sustained glacial conditions for the YD timelines. In addition, Mahaney et al. (2013b) argue that Earth may have experienced a sustained bombardment by fragments of the Taurid Complex following the 12.8 ka airburst (Napier 2010), such that a long-term, negative downturn in Earth's heat budget, could maintain a glacial positive mass balance. Here, paleosol and weathering-rind information combine to offer supportive evidence of a cosmic airburst over the Western Alps firming up its connection to the YDB.

Many geologists, infused with the notion of uniformitarianism, as proposed by Lyell (1830), are reluctant to entertain a possible catastrophic mechanism for the YD (Kennett et al. 2007), that is, a cosmic event to explain changes in the earth-atmosphere system such that solar-induced warming might be offset for nearly 1300–1400 years by the YD glacial advance. As discovered by palynologists decades ago, a drastic change in the

distribution of a widespread cold-loving alpine wildflower, a member of the rose family—*Dryas octapetala*—causing it to expand its area of coverage, thus increasing for a time its pollen count in retrieved cores, lent its name to the Late Pleistocene YD climatic episode. Because the Mt. Viso Massif, one of the highest areas in the Western Alps, is surrounded by valley glaciers that responded to off-again, on-again rapid changes in snow balance at the end of the ice age (Würm in the Alps, Pinedale in the Rocky Mountains; Liki on Mt. Kenya), it is an obvious laboratory in which to study the YD in relation to earlier warming (LG) and late Holocene cooling (LIA).

The 12.8 ka age of the YDB, based on Bayesian chronological analysis of Kennett et al. (2015), places the maximum age of the last stadial of the Late Pleistocene, on firm ground. AMS radiocarbon places the age between 12,735 and 12,835 Cal B.P. averaged to 12.8 ka, an abrupt contact coincident with the black mat evidence on several continents. According to Lohne (2013, 2014), over one hundred ^{14}C ages from the Kråkenes Core (western Norway), average $12,737 \pm 31$ cal yrs BP for the YD basal age in lake sediment (Mangerud 2021). Because these 118 dates match ages from dozens of black mat sites on several continents, 12.8 ka is a standard for the YDB. Despite the age synchronicity—terrestrial to cosmic—and the abundant airburst evidence of Firestone et al. (2007), Wittke et al. (2013), Mahaney et al. (2013b, 2018,); Wolbach et al. (2018a, 2018b, 2019); Pino et al. (2019), Moore et al. (2020), workers, such as Broecker et al. (2010), Meltzer et al. (2014), Holliday et al. (2009), and others argue against a cosmic origin for the YD for a number of reasons. In particular, they dispute the catastrophic connotation and disjunct age relationship of 12.8 ka to the megafaunal extinction and disappearance of the Clovis culture. A measured response to Holliday et al. by Wolbach et al. (2019) stressed the isochronous C14 for black mat sites, thus refuting their inaccurate age claims. However, critics of the airburst hypothesis continue to champion other mechanisms, namely a shift in marine currents (i.e., the Gulf Stream), which by itself would not produce worldwide climatic-biotic-hydrologic adjustments leading to ice advances globally, and even adjustments in the Antarctic Ice Sheet. A near-instantaneous termination of the Allerød interstadial-startup-of-the-YD-ice-advance falls certainly within the catastrophic range of one other mechanism, namely, continual Earth-Encke Comet interaction following the impact/airburst over Manitoba that conceivably could interact with marine current cooling to produce the time required to maintain YD cooling. The spread of affected airburst sites, oriented southwest to east-northeast, suggests the Encke comet approach was from the north. The current Holocene/Pleistocene transition currently set at 11.6 ka following termination of the YD is firm enough but some thought might be given to the Allerød interstadial/YDB at

12.8 ka representing the Allerød/YD–interstadial–stadial transition, two major climatic shifts of the LG-YD.

Black Mat sediment/relative age control

For reasons already outlined, absolute dating of relevant sections in the Viso Massif area is not possible and none is expected in glacial terrain where moraine deposition tends to abrade and destroy sediment containing radiocarbon datable materials. Even areas with lacustrine and mire covers near G12 in the South Cirque (Fig. 2a) and near G5 (Fig. 2b) yield radiocarbon datable core material, that is either too young to add to the scenario unfolding here or consists of sediment lacking organic carbon content. However, the LG sediments of mid- to late Allerød age, in the stillstand complexes of the Guil south and north cirques and the upper Po drainage, had to have been in place to receive the full effect of released heat and pressure at the YDB. It is these sections which contain the bulk of cosmic-affected sediment infused after only a few centuries exposure to the subaerial atmosphere after glacial retreat, and it is these thin Entisols (A/Cu; Ah/C/Cu) that survived widespread airburst to release affected sediment to wider dispersal as soils evolved into paleosols. Since the areas up-valley from the stillstand moraines are either exposed bedrock or covered with younger Holocene-age sediment, we sampled only selected YD moraines to determine how much cosmically affected sediment was entrained and reworked by YD ice. After reviewing ferrous and non-ferrous base metals—Fe, Ni, Co, Cr—only Fe in G22 and G27 come close to rivaling the LG sections in Guil south (Fig. 2a); none appear elevated from YD to LG in Guil north; and while Fe is somewhat elevated in the LIA group, none of the remaining elements are different from the LG or YD samples. Within the Pt elements, only the LG was analyzed in Guil South and North; and the upper Po samples show Pt greatly elevated in all V sections, higher in V9 (lower subsoil), close to crustal average in the YD, and very high in V13 of the LIA, with high Ir throughout the LIA and in V10 of the LG.

While we can show clearly elevated base metals in some LG sites, many with disparate concentrations in the YD, it seems clear the latter represent sediment reworking. Within the Pt group elevated Pt/Pd ratios are high and variable throughout the LG group in all three cirques. The Pt/Pd ratios dominate in the LG samples in Guil South; Pt/Pd is overall higher in the LG of Guil North, with G11-Bw higher by an order of magnitude, and the YD low or with no detection; LG in the upper Po sequence of Pt/Pd shows a staggered concentration from 0.7 to 8.0. Within the Po LIA, Pt/Pd presents with a wide range of concentrations, from near 1.0 to ~57. In the lower Po, site V24 shows minor variations from near 1.0 to 2.2 with little difference between the LG and YD paleosols. Concentrations of Ir across selected

samples in all cirques yield values of $\times 2$ – 3 in the LG relative to crustal average in Guil South. Concentrations in the LG of Guil North is $\times 3$ – 8 , nil in the YD; concentrations $\times 6$ – 8 in V10, all others no detection. Iridium was not analyzed in the paleosols of V24. Thus, the relative age of sediment places the LG in all three cirques with at the most 300–500 years of weathering and soil formation during the mid-Late Allerød prior to the projected airburst.

A summary of all black mat cosmic signatures known up to 2018 was published by Wolbach et al. (2018a, b), entered here as Fig. 9, captures scattered sites on several continents, some dated by AMS C14, others by RD methods, still others by ambiguous dating. Not all sites carry the iconic black

bed (as in the NW Andes, Mahaney et al. 2013b), others relegated to redistribution of affected minerals in LG soils to present-day paleosols. The present-day record contains left-over grains following weathering of soluble constituents and masking of others with carbon/Fe coatings. Soot content in site V10, upper Po River (see Viso group above), was the highest of all sites tested in Europe up to 2017 (Allen West, personal note, see comparison to other intercontinental sites, Fig. 9). In addition to signatures itemized in Fig. 9, melted/welded quartz (Fig. 7b), one of the major proxy indicators of a cosmic event in the Mt. Viso paleosols, requires a temperature of ~ 1700 °C to form. Indurated sands, comprising a mixed lithology composition (Fig. 7a), rank with

SITES (35)		Modelled ages	Uncertainty (68%)	AC/Soot peak	Charcoal / ash peak	Carbon spherules peak	Glass-like carbon peak	Fullerenes peak	PAHs peak	Dark layer (black mat)	Platinum peak	Fe-, Si-rich spherule peak	High-temp melt-glass peak	Nanodiamonds in sed.	Nanodiamonds - CSGLC	Ir, Os, Ni, Co, Cr peak	Extinct megafauna	Human pop decline
WELL-DATED YDB SITES with BIOMASS-BURNING PROXIES																		
Aalsterhut	12780	35		•	•	•		•										
Abu Hureyra	12825	55	–	•	•	•		•		•	•	•	•	•				
Arlington Cyn	12805	55	•	•	•	•		•		•	•	•	•	•		•	•	
Blackville	12820	1080		•	•	•		•		•	•	•	•	•				
Blackwater Draw	12775	365	–	•	•	•	•	•	•	•	•	•	•	•		•	•	
Bull Creek	12840	75	•	•	•	•		•		•			•					
Daisy Cave	12730	320	–	•	•	•	•	•	•	•								•
Guil-Mt. Viso	12787	34		•	•	•		•		•	•	•	•	•				
Indian Creek	12750	425		•	•	•		•		•	•	•	•	•			•	•
Lake Cuitzeo	12850	570		•	•	•		•		•	•	•	•	•		•	•	
Lake Hind	12745	180	–	•	•	•		•		•	•	•	•	•				
Lindenmeier	12775	180		•	•	•		•		•	•	•	•	•		•		
Lingen	12735	85		•	•	•		•		•	•	•	•	•				
Lommel	12735	790	–	•	•	•		•		•	•	•	•	•				
Melrose	12255	2405	•	•	•	•		•		•	•	•	•	•				
Mucunuque	12787	34		•	•	•		•		•	•	•	•	•				
Murray Spgs	12750	235	•	•	•	•	•	•	•	•	•	•	•	•		•	•	
Ommen	12750	560		•	•	•		•		•	•	•	•	•				
Parangueo Lake	12843	228		•	•	•		•		•	•	•	•	•				
Santa Maira	12785	295		•	•	•		•		•	•	•	•	•				
Sheriden Cave	12840	120		•	•	•		•		•	•	•	•	•		•	•	
Stara Jimka site	12805	70		•	•	•		•		•	•	•	•	•				
Talega	12860	150		•	•	•		•		•	•	•	•	•				
Topper	12785	185		•	•	•		•		•	•	•	•	•				•
INADEQUATELY DATED YDB SITES with BIOMASS-BURNING PROXIES																		
Audenge	–	–		•	•	•		•		•	•	•	•	•				
Caspian Sea	–	–		•	•	•		•		•	•	•	•	•				
Chobot	–	–	–	•	•	•		•		•	•	•	•	•				
Gainey	–	–	–	•	•	•		•		•	•	•	•	•		•		
Halls Cave	–	–	•	•	•	•		•		•	•	•	•	•				
Kangerlussuaq	–	–		•	•	•		•		•	•	•	•	•				
Kimbel Bay	–	–		•	•	•		•		•	•	•	•	•				
Morley	–	–		•	•	•		•		•	•	•	•	•		•		
Newtonville	–	–		•	•	•		•		•	•	•	•	•				
Paljan	–	–		•	•	•		•		•	•	•	•	•				
Paw Paw Cove	–	–		•	•	•		•		•	•	•	•	•				•
Watcombe Bottom	–	–		•	•	•		•		•	•	•	•	•				
TOTALS				6	34	24	20	3	3	27	15	29	8	12	14	12	6	10

Fig. 9 Cosmic signatures in the sedimentological record recorded at black mat sites on several continents. Of particular interest are the signatures recorded at the Guil-Mt Viso and Mucunuque sites. Mucunuque in the northwestern Andes is dated by AMS C14; the Mt Viso sites in the Western Alps are dated by RD (relative dating) methods

based on glacial sediments of Allerød age (~ 14 – 12.8 ka), the last interstadial of the Late Glacial. The sediments affected were soils in the initial stage of morphogenesis, not more than ~ 500 yr into their weathering cycle, their profiles later enlarged by re-distribution of affected materials added to by airfall input of allochthonous sediment

melted/welded quartz across the paleosols studied here. Air-quenched grains (Fig. 7c) are less common across the paleosol populations studied here but underscore the P/T forces at work to source, modify, transport and deposit minerals on time scales of seconds/minutes etc. The indiscriminate testing for Pt and Pt/Pd across the paleosols, followed up with Ir when Pt/Pd warranted, indicates a random distribution of Ir (Tables 4, 5 and 6) with concentrations many orders of magnitude above average crustal concentrations.

Clay mineralogy

The scattered mica (Fig. 8a–c) might be expected to weather to vermiculite—smectite, as expected from weathering of Al-vermiculite in northern regions (Bain et al. 1990), or randomly interstratified illite-vermiculite from illite (Hong et al. 2014; Bonifacio et al. 2009), over the 11–12 kyr time frame for these sections. However, the gabbro-ophiolite-talc-serpentine-marl-rich sediments do not produce observable trends from the Ah to Bw horizons where most chemical reactions take place. The overall clay content is relatively low, in some cases to near 1%, and despite pH in the 5–6 range, the soils appear inert to even medium scale transformations. Slight increases in smectite with depth, in G3, G3A, G11, among other sections, might relate to mica weathering, but a clear trend is not present in the database. The overall distribution of clay species supports measurable pre-weathering, translocations of both primary and secondary minerals to sections under investigation, and minor transformation in situ. The primary species—talc and serpentine—both Mg silicates have origins in the foliated rocks all over the Western Alps, and little relationship to the secondary species. The chrysotile component of serpentine, widespread in the region, poses a significant health hazard from mining and tunnel construction.

Smectite, however, with its expandable lattice, reservoir of H₂O, and stray cations offers a micron-size environment in which microbes may thrive and proliferate. We hypothesize that P–T from an airburst, diversionary P cones, coupled with variations of T from the airburst, might have affected the evolutionary path of microbial populations resident at time of the airburst. To test this hypothesis, we used DGGE analysis on samples from several sections with the intention to look for anomalous meta-genomic structures, finding only one such 16S rRNA population in site G3, specifically in the Ah (surface) horizon (see Fig. 4) (Mahaney et al. 2013a). Furthering this analysis with other samples, the relation of REEs to bacteria in the Guil-N sample group, Young et al. (2019) suggested the latter rely on specific elements, specifically REEs as electron receptors, important controllers in microbe respiration processes. Extending this research to full meta-genomic limits using functional genes in paleosols, spread across a wide arc in all three catchments, portends

to offer new scope to microbe phylogeny and its probable relation to extraterrestrial forces, testing the limits of life itself. Each sample analyzed for functional genes presents new information on the potential link between the geological environment and the precise composition of the microbial community. Doubtless, many undiscovered links of this type are to be found—and may suggest an extraterrestrial impact on present-day community structures. Linking bacterial cells to individual clay minerals, for example, one clay species at a time could open a new field in molecular geobiology.

Paleosols

The paleosols, whether of LG or YD age, carry the same profile divisions of Ah/Bw/Cox/Cu horizons, occasionally as at G9 with Ah/Bw/Cox/R (R = bedrock). The progression from thin weathered beds, to A/C, A/Cox, Ah/Cox/Cu, leading to profiles with B horizons is best outlined in Mahaney et al. (2016a), the original thin A/C or Ah/Cox profiles considered similar to surface weathering entities in existence at the time of the presumed airburst of or close to 12.8 ka. As usual with glacial sediment, dating by AMS C-14 or conventional means, is always fortuitous in locating places where existing bogs or soils have been overrun by advancing ice. In these cases, much depends upon whether in situ sediment is frozen or water saturated. If frozen, and with sediment armored (Mahaney 2002), stress is not sufficient to strain materials encountered; if water saturated, the pressure exerted by ice is hydrostatic, and materials encountered show no strain. The latter example may explain why so many buried soils exist on Mt. Kenya where glacial advances encountered water logged organic sediment (Mahaney 1990). While we lack suitable situations of moraine-over-organics allowing C14 age dating of the cosmic-affected sediment in question, we can place such deposits well within the Late Allerød (13 ka), just prior to the YDB. All sections exposed coarse clastic contents with matrix materials consisting of sand and silt with minimum clay content. And despite centuries of transhumance and fluctuating freeze–thaw cycles in winter, no convoluted horizons were encountered, horizon contacts more or less level with the landform surface, some showing only minor disturbance most probably from throughput of soil moisture over time. Freeze–thaw processes might be held to a minimum given the lack of clay and thickness of snow cover, the latter an insulating blanket.

Soils existing during the Allerød, despite thin profiles, would have contained clast heavy surfaces, mass of clay poor and silt-sand heavy content that responded to heat and pressure in a variety of ways. The likely thin profiles are schematically shown in Mahaney et al. (2016a), and as indicated some materials were compressed downward, and others rendered volatile, were melted, welded, and from the available data presented with air-quenched characteristics following

low cooling time in the atmosphere. Any carbon existing in these soils would have been volatilized forming opaque and spherule microforms on pebble and sand clasts found in the existing paleosol mass. The distribution of affected sediment was randomized by P/T (pressure and heat) vectors, such that some sections contain almost uncountable specimens, others with less, some with most affected material near the surface while in other sites most material is located down-section or even in the Cu (parent materials) horizons. Mostly, paleosols with matrix materials registering Pt, and with Pt/Pd ratios above 1.0, also contain Ir, sometimes with the latter element registering with a concentration above an order of magnitude higher than crustal average.

Geochemistry

Despite changes in lithology across the catchments, there are a number of common chemistries to report, which add to the environmental inventory of LG → YD → Neoglacial sediments, and their weathering histories. For one, the Si:Al ratios of 2:1 match the reported clay mineralogies with the obvious exception of 1:1 species, i.e., kaolinite. Si varies a little but does not show abnormal movement, unlike Al which is quite variable, higher in Guil S, lower in Guil N and in the Viso samples. Likewise, Ca and Na, two highly mobile macro-elements, show variable dissolution effects in the surface epipedons of all the paleosols. This is followed to some degree by Mg and to a lesser degree by K, as expected given their relative mobility. As indicated with the chemical analysis there is no indication of aeolian influx despite the fact that the particle-size analysis shows some profiles, most notably G26, G29, G3, G4, G9, G11, V20, V22, V24 surface, V24 (buried), to have fining upward sequences within the silt fraction. Yet, nothing stands out in the chemistries of these sites to identify an aeolian component which suggests the loessic input must be mostly local, no allochthonous segment with extraneous chemistry.

Pitching the three sample groups together, the data depict relatively high amplitude of element elevations above average crustal concentrations with little preference for LREEs or HREEs to group up. It is remarkable, but not explainable, that Th is higher than average in Guil S, relative to Guil N and the Viso group. The staggered distribution of elevated REEs, Pt and Ir within and between paleosols reflects, at least to some degree, the pathways of pressure and heat emitted by the airburst reforming in situ minerals as well as incoming cosmic materials combined. Some of the highest Pt and Ir elements are found in mixed sections in Guil N and S and in the Viso group, the lower Po valley samples (V24) seemingly to have escaped any direct effects. The LIA of the Viso group is seen to carry high magnitude effects from the airburst, its source position likely on the water divide-arête of France and Italy well situated to receive maximum heat

and pressure. Elevated concentrations of cosmic elements in YD deposits measures the effects of overall reworking of sediments as expected.

Correlation to worldwide evidence

As described elsewhere, in the Antarctic (Mahaney et al. 2018) and the Arctic (Petaev et al. 2013; Andronikov et al. 2016), and in other lowland areas (Firestone et al. 2007, 2010; Israde-Alcántara et al. 2012; Mahaney et al. 2017; Wolbach et al. 2018a, 2018b; Thackeray et al. 2019; Pino et al. 2019; Moore et al. 2020), the cosmic-affected sediment includes high-temperature carbon and Fe spherules, charcoal, soot, glass-like carbon, nanodiamonds, melted, welded and air-quenched grains), often with elevated REEs, and Pt elements including Ir. Despite variations in nano-diamond occurrences (Kinzie et al. 2014), and varying evaluation of microspherule databases (LeCompte et al. 2012), biomass burning (high soot content in Viso paleosols), climate change (YD) and megafaunal extinctions come together as near interconnected events centered on the YDB. With widely distributed sites across much of Europe, the Middle East, North and South America, Africa and Antarctica, in the Alps, this cosmic event was accompanied by a rapid change from negative to positive glacier mass balances, resulting in the Younger Dryas ice advance. To test for age equivalence between the Alps and other sites, here we combine glacial sedimentation with weathering, and production of early soil development leading up to the end of the Allerød and the YDB. In this instance, as in all others worldwide, glacial retreat during the Bølling-Allerød, in league with the insolation curve, was abruptly interrupted at or near the Allerød/YD transition with a sharp warming reversal from interstadial to stadial conditions. As discussed previously, seminal work by Kennett et al. (2015), using Bayesian chronological analyses, produced consistent synchronous ages of 12,835–12,735 Cal B.P.; hence, 12.8 ka is a firm average for the Younger Dryas boundary. While our data fall just outside this narrow one-century transition, our timeline for weathering/soil morphogenesis is well within a ~3–4 century lead-up to the LG/YD, coupled with stratigraphic superposition of YD/LG moraines, and widespread but variable distribution of cosmic-affected surficial sediment.

Whereas we hypothesize that the theorized cosmic event was caused by an airburst fragment or fragments sourced from Earth's encounter with the Encke Comet (12.8 ka) (Napier 2010), thereafter exploding over the Mt. Viso area, while others argue that such an encounter could not sustain the cooling event that followed. The Earth/comet impact is thought to have occurred over southern Manitoba, melting part of the Laurentide Ice Sheet in the process, spewing fragments southward in an arc southwest to east–north-east. Other fragmental bodies of the impact continued to

encounter Earth as the Taurid meteors. As hypothesized further by Mahaney et al. (2013b), during the YD, -12.8 ka to ~ 11.6 ka, the meteor swarm was possibly of sufficient mass to maintain positive glacial mass balances in various alpine localities in North and South America and in the Alps, thus sufficient to sustain the YD glacial resurgence linked to the main cosmic event. Whether the YD cooling event was caused conclusively by one or the other—the thermohaline circulation or the widespread fragmental explosions—the upshot is that the YD is firmly documented by palynological and geological evidence on a worldwide basis. The marine argument by itself does not explain the worldwide YD effect, but it does reinforce regional cooling and augment intercontinental cooling imposed by instantaneous fragmental airbursts.

Yet, critics of the YDB cosmic hypothesis, despite increasing worldwide evidence from far flung sites, fail to support catastrophic cosmic evidence for the onset of the last Pleistocene stage, the YD. In large part, the argument that changes in the Gulf Stream is a better fit to explain the YD, such oceanographic changes are limited to regional areas, while the cosmic evidence reported here is not only intercontinental, it rests upon occurrences reported in a wide arc south from Manitoba, and growing exponentially. Combined with the argument that the YDB airburst event could not possibly generate a glacial advance lasting over 1 kyr, such was discounted by Lowe et al. (2008) and Teller et al. (2002) who invoked the well-established feedback loops in the thermohaline circulation systems, such that once the warm circulation ceased in the North Atlantic, systemic inertia caused a delay of ~ 1400 years before normal circulation resumed. Critical arguments against the airburst hypothesis fail to consider that the main impact event itself likely contributed to the draining of Lake Agassiz which affected the thermohaline circulation cooling the North Atlantic region. Moreover, the 1400-yr lag in restarting the Gulf Stream was likely assisted by the slow advancing fragmentation of the Encke Comet (Taurid Meteor), which together may have operated to maintain a negative downturn in Earth's heat budget, resulting in the production of YD cooling and generation of glacial positive mass balances worldwide. Here, we present paleosol and weathering-rind information that not only provides supportive evidence of a cosmic airburst over the western Alps, it brings paleosols, often overlooked, into the mix of other surficial geological databases that collectively owe their existence to a catastrophic event.

Beyond paleosols, airbursts have played a large role in affecting landscapes and history if you consider: the Tamm el-Hamm airburst of 1650 BCE (~ 3600 years ago), over the Jordan Valley that destroyed a major city (Bunch et al. 2022); The Hopewell airburst event of 1699–1567 years ago (252–383 CE) that destroyed a large area over the Ohio River Valley in the Late Holocene (Tankersley et al. 2022);

and the Tunguska Event of 1908 that laid waste to 2200 km^2 of Siberia (Svetsov 1996), all suggesting cometary impacts are random but devastating events. Still beyond all this, considering the data presented here, the LG/YD climatic hypothesis, supported by dozens of parallel black mat sites, might follow the continental drift/plate and Anthropocene warming hypotheses—first disavowed, tentatively accepted, to fully endorsed status (Powell 2022). Given studied black mat sites worldwide, isochronous C14, and relative age dating controls for a singular event, all support the 12.8 ka YDB.

Conclusion

On a weathering-pedological basis, it is impossible to clearly identify changes from the LG to YD pedostratigraphic sections using normal weathering criteria, whereas the mid-Neoglacial to LIA sections either yield lower grades of weathering as in the Viso sequence or higher grades in Guil S. As expected with prevalent volcanic/metamorphic lithologies, and overall lack of mica, clay mineral genesis is attenuated with low clay concentrations, while silt concentrations in most LG-YD sections tend to increase in paleosol Bw horizons suggesting that airfall influxed sediment tends to move downward with throughput of soil water. Testing the source of silt using REE concentrations across the sections in both basins proved inconclusive rendering the silt fraction autochthonous.

YD sediments are identified in Guil North where LG moraine (G3, 3A, 9, and 11) are clearly overlain with YD moraine (G1, G2). In Guil South (Fig. 1) the YD can be traced down valley from Lake Lestio to site G29 with no deposit superposition, excepting where mid-Neoglacial (G28) to LIA (G27) deposits lie unconformably on YD substrate. In the upper Po Basin, recessional moraines of LG age lie intersected by mass wasted deposits, mainly along the south-facing slopes; the lower north-facing slopes between 2250 and 2300 m were overlain with deposits of YD age ice issuing from a couloir on the NE slopes of Mt. Viso. The combined LG-YD deposits in the upper Po valley are clearly distinguishable on the basis of topographic position, traceable across large volume rockfall and landslides, and close correlation of weathering-rind measurements. Chemical alteration of sediment (CIA) values in LG-YD deposits, despite marking a time hiatus, LG-YD sediment complexes, as expected, show similar weathering indices.

Because the YD climate reversal occurred at the end of insolation-driven warming during the LG, it has been a source of multiple hypotheses over the years—some chrono-driven to derive bracketing ages, others to explain the major climate shift with detailed pollen analysis. Our hypothesis of recent coupling of the YD event with

a cosmic airburst occurrence over the Viso Massif rests on evidence written into the Allerød moraine surfaces in Guil N. Since the cosmic hypothesis has proved a contentious issue among various researchers, we used a test of normal stratigraphic parameters that might support or negate a cosmic connection. Because the initial cosmic data came from Guil N, we expanded efforts across all three major cirques—Guil N, Guil S and Upper Po—added with sections previously examined, we could find nothing out of the ordinary with regard to section disturbance, horizon convolutions and or color variations. However, as matrix sedimentary materials in paleosols have readjusted over time, with normal weathering processes in play, we did find affected sediment to have undergone random re-distribution downward. We did find fractured surface clast rinds, and within paleosol horizons, melted features, welded spherules of Fe and C similar to other published research in Guil N. Resampling of sites in Guil N, coupled with Guil S and the Upper Po catchment, showed that whereas REE analysis was variable in support of cosmic interference, elevated concentrations of Ni, Fe, Co, Cr and Cu along with Pt and Ir as partial coatings in both rinds and sands support the cosmic hypothesis. In summation, the available data support conflagrated LG sediments with above crustal average concentrations of base metals, variable REEs, Pt, and Ir, all support an airburst of a fragmentary particle or particles over mid- to Late Allerød surfaces around the Viso Massif. The YDB age, on the Viso Massif, rests upon the probable mid- to late Allerød age of the LG sediment in question. Further, we postulate that the Allerød surface, under an initial weathering stage carried a wet surface with an early seral stage of plant growth, which provided available carbon to the airburst. Despite the reluctance of some to overcome aversion to catastrophic events, the evidence in this case supports a one-time instantaneous cosmic event that redirected a warming event into full scale reversal, such that re-advancing ice reached to near the stillstand positions of former LG glaciers. Thus, it seems, in some cases, catastrophic events disturb the norm of slow-moving geological processes, perhaps more so than previously thought.

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Declarations

Conflict of interests This research has not received funding from outside sources. There is no competitive interest to state and the paper has not been sent to another publication. This research is the product of work carried out previously over several decades and the data availability resides in my lab files and computer hard drives. I also state that all co-authors played different, but key roles, in bringing this summary article to its final state. Peeter Somelar and Chris Allen assisted in the field and the laboratory and supported the work with grants and their laboratories. Peeter did much of the mineral and chemical analyses using equipment at Tartu University, Tartu, Estonia. Chris did the meta-genomic work at Queens/Belfast which identified the bacteria anomaly identified in the ms. and he is continuing work on functional genes in selected sections in all three catchments identified in the ms. I carried out numerous analyses over the period 2004–2022, first in my laboratory at York University, and thereafter in my laboratory at home, and at the University of Toronto, Depts of Materials Science, Geology, as well as Surface Interface Ontario's lab in Chemical Engineering. We all produced grants over the years to fund the research work, and in some years, I funded the project out-of-pocket, with additions from York University and the National Geographic Society. Peeter, Chris and I form the base team. Two others—Prof. Dave Krinsley (Oregon) and Prof. Volli Kalm (Tartu U., Estonia)—full partners who worked with us in this endeavor are sadly deceased since 2017.

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