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Surface vitrification caused by natural fires in Late Pleistocene wetlands of the Atacama Desert

Pierrick Roperch^a, Jérôme Gattacceca^b, Millarca Valenzuela^c, Bertrand Devouard^b, Jean-Pierre Lorand^d, Cesar Arriagada^e, Pierre Rochette^b, Claudio Latorre^{f,g}, and Pierre Beck^h

^aGéosciences Rennes, CNRS-INSU, Université de Rennes1, Rennes, France

^bCNRS, Aix Marseille Univ, IRD, Coll France, CEREGE, Aix-en-Provence, France

^cInstituto de Astrofísica, P. Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile

^dLaboratoire de Planétologie et Géodynamique, Nantes, France, UMR 6112; Université de Nantes, Faculté des Sciences, 2 Rue la Houssinière, 44322, Nantes Cedex, France

^eDepartamento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Plaza Ercilla 803, Santiago, Chile

^fCentro UC del Desierto de Atacama and Departamento de Ecología, Pontificia Universidad Católica de Chile, Alameda 340, Santiago, Chile

^gInstitute of Ecology & Biodiversity (IEB), Santiago, Chile

^hInstitut de Planétologie et d'Astrophysique de Grenoble (IPAG), 414, Rue de la Piscine, Domaine Universitaire, 38400 St-Martin d'Hères

25

26 **ABSTRACT**

27 We describe extended occurrences of unusual silicate glass surface layers from the
28 Atacama Desert (Chile). These glasses, found near the town of Pica at four localities
29 separated by up to 70 km, are neither fulgurites, nor volcanic glasses, nor metallurgical
30 slags related to anthropic activity, but show close similarities with other glasses that
31 have been attributed to large airbursts. ^{14}C dating and paleomagnetic data indicate that
32 the glasses were formed during at least two distinct periods, and that they are restricted
33 to specific Late Pleistocene terrains: paleo-wetlands and soils rich in organic matter
34 with SiO_2 -rich plant remains, salts and carbonates. This rules out the hypothesis of a
35 single large airburst as the cause of surface melting. Large oases did indeed form in the
36 hyperarid Atacama Desert due to elevated groundwater tables and increased surface
37 discharge during the Central Andean Pluvial Event (roughly coeval with the Mystery
38 interval and Younger Dryas). Burning of organic-rich soils in dried-out grassy wetlands
39 during climate oscillations between wet and dry periods rather than a large airburst
40 explains the formation of the Pica glasses. Finally, we discuss the implications of our
41 results for other surface glasses previously attributed to extraterrestrial events.

42

43 **Keywords.**

44 Silicate glass, airburst, Wetland, Pyrometamorphism, Younger Dryas, Atacama Desert

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1. Introduction

Impact glasses are a common feature associated with many terrestrial impact structures (French and Koeberl, 2010). Most meteoroids disintegrate during their entry into the Earth's atmosphere. The Chelyabinsk (Brown et al., 2013) and Tunguska (Svetsov and Shuvalov, 2008) airbursts were the most recent and best described examples of strong airbursts but these events were in the low energy range without significant thermal effects on the ground. Numerical modeling suggests that the energy released by the largest low-altitude airbursts of cosmic bodies (asteroids, comets) during their entry into the Earth's atmosphere could be sufficient to produce large catastrophes (Boslough and Crawford, 2008). Indeed, a large comet airburst has even been proposed to have caused Younger Dryas cooling (Firestone et al., 2007; Bunch et al., 2012; Wittke et al., 2013), an explanation that has garnered considerable opposition (see Surovell et al., 2009; Pigati et al., 2012; Boslough et al., 2013). Melting of the soil surface by radiation from large aerial burst has also been proposed (Wasson, 2003; Boslough and Crawford, 2008) to explain the formation of some anomalous silicate glasses like the Libyan Desert Glass (Barrat et al., 1997; Kramers et al., 2013). Other examples include Miocene glass deposits found in the Argentine pampas (Schultz et al., 2004) as well as Pleistocene scoriaceous glasses from Australia (Haines et al., 2001) (Edeowie glass, age 0.6 to 0.8Ma) and northern Africa (Osinski et al., 2007; Osinski et al., 2008) (Dakhleh glass, age 145 ± 19 ka). French and Koeberl (2010) point out that it is often difficult to assert an impact origin to such glasses, which closely resemble non-impact glasses such as fulgurites, volcanic glasses or even metallurgical slags. The origin and mechanism of formation of these glasses is thus strongly debated. Hence, proving or disproving the impact origin of these glasses has implications for estimating the flux of airbursts producing bolides to the Earth.

Massive glass blocks (called Pica Glass, PG) were recently discovered (Blanco and Tomlinsson, 2013) lying on the surface along the eastern margin of the Tamarugal-Llamara basin in the Atacama Desert, Chile (Fig. 1). They were interpreted as the consequence of a major airburst (Blanco and Tomlinsson, 2013). We present field and petrographic observations, as well as ^{14}C dating to further constrain their origin. Paleomagnetism is used here to complement ^{14}C dating, as it can be used to test the synchronicity of the glass formation at the different locations. The paleomagnetic study of the PG and underlying baked clays also constrains the temperature reached by the clays, and the ambient magnetic field during glass formation. It is also a test for the origin of the PG as fulgurites. Indeed, lightning strikes create strong magnetic fields (>100 mT) that result in specific remagnetization of the surrounding rocks (Graham, 1961).

2. Geology and field observations

Dark green, vesiculated (up to 50% vesicles in volume) and irregularly shaped, tabular glassy bodies occur scattered on the surface at several localities roughly aligned in a North-South direction and separated by more than 70 km. Here, we will only discuss observations made at four localities (Puquio de Nuñez, Quebrada Chipana, and Quebrada Guatacondo, and NW of Pica) (Fig. 1). Individual blocks up to 50 cm wide and 1 to 30 cm thick are scattered over areas up to 1 km^2 in extent (Fig. 2, 3). Their glassy texture demonstrates high temperature melting and quenching.

At Puquio de Nuñez, north of the small oasis of Puquio de Nuñez (Fig. 2a), the glasses are distributed over a large $\sim 2\text{ km}^2$, almost flat surface (elevation 1200-1210 m) of late Pleistocene paleo-wetlands deposits (Blanco and Tomlinsson, 2013; Blanco et al., 2012) covering a Miocene tectonic flexure on the western border of the basin, which is filled by Neogene sediments (Nester, 2008). Glass blocks are distributed unevenly and locally

concentrated over surfaces up to several tens of meters across (Fig. 2b). Such concentrations are more frequent on tops of small ridges or ground mounds. Glasses are also found in the sandy soil covered by a ~10 cm thick layer of sand (Fig. 2e). Some samples present a striated surface with numerous quartz grains embedded in mm-sized holes, grooves and tube-shaped cavities that are remnants of plants such as twigs and roots (Fig. 4; Supplementary Fig. S1).

Puquio de Nuñez is presently a very small and mainly artificial (i.e. it has been dug out) oasis just a few tens of meters wide. Water wells, drilled ~300 m to the east of Puquio de Nuñez, penetrate the water table located several meters below the present-day arid surface. A sub-surface fault probably impedes the flow of ground water to the west bringing it close to the surface in this area. The Puquio de Nuñez area was from time to time a more humid area in the past (Blanco et al., 2012), when the water table reached its highest level.

At Quebrada de Chipana, located ~35 km south of Puquio de Nuñez, glasses are found in two separated fields (Fig. 3a). To the west, PG of variable size up to 50 cm thick are scattered at the surface (Fig. 3b, c). To the east, PG are found directly overlying red clay sediments that correspond to an old terrace with an overbank clay deposit along the intermittent stream of Quebrada de Chipana (Fig. 3d, e, f). The clay deposit has been partly eroded or covered by younger deposits but the best remains can be observed *in situ* with a thickness of about 10 to 30 cm (Fig. 3f). Although erosion has broken up most of the silicate glasses from the baked clays, we can still find evidence of several glasses in their *in situ* position just above the clay layer. Silicified plant twigs and imprints are common in the baked clays (supplementary Fig. S1). A 20-30 cm thick layer of buried plant material is frequently associated with the glasses (Fig. 4a; supplementary Fig. S1). Fossil plants, currently composed of silica (50%) and carbonates (20%) with almost no

residual organic matter, are often mixed with or underlie the baked clays or the glasses (Fig. 4c, d; supplementary Fig. S1).

At Quebrada Guatacondo, most of the glasses are found north of the Quebrada (intermittent stream), a few meters above the present-day base level of the stream. The PG layer is more discontinuous than at the two previous sites (Puquio de Nuñez, Quebrada de Chipana). Glasses are sometimes found above and below a 10-20 cm thick white layer composed mainly of burnt but not melted silicified plant remains (Supplementary Fig. S1). Glasses above the white layer consist mainly of melted silicified plant twigs. The largest PG blocks, up to 30 cm thick, are found within the soil below the white layer. Plant remains and plant imprints are also observed in the glasses formed within the soil (Supplementary Fig. S1c, d).

Isolated blocks of PG also occur near and within the town of Pica, but these blocks could have been transported from their original location. Abundant *in situ* glasses are found about 9 km to the NW of the town of Pica. The glasses are spread over about 1 km at the base of the southern and eastern edges of low-lying hills. These hills, related to a tectonic fault (Blanco et al., 2012; Blanco and Tomlinsson, 2013), limit a paleo-wetland deposit to the west with a mean elevation of 1100m. Burnt soils without glasses are also observed on the surface in the same general area.

At all localities, most glasses contain plant imprints or silicified plant remains (Fig. 4; supplementary Fig. S1).

3. Petrography, mineralogy, geochemistry

3.1 Samples and Methods

Microscope observations were made on polished thin sections in transmitted light and reflected light. The samples were then observed with scanning electron microscopes

150 (JEOL JSM 7100F with energy dispersive x-ray spectroscopy (Oxford EDS/EBSD) at
151 University of Rennes1, and Hitachi S-3000N SEM, at CEREGE, operated at 15 kV, and
152 fitted with a Bruker X-Flash detector and SPIRIT EDS system).

153 Whole-rock chemical analyses for 13 samples of PG, one sample of silicified plants and
154 one soil sample were acquired at the Service d'Analyse des Roches et des Minéraux
155 (CRPG) by ICP-OES for the major elements and ICP-MS for the trace elements and REE.
156 Sample preparation, analytical conditions, uncertainty and limits of detection are
157 detailed in Carignan et al. (2001) and in [http://helium.crpq.cnrs-](http://helium.crpq.cnrs-nancy.fr/SARM/pages/roches.html)
158 [nancy.fr/SARM/pages/roches.html](http://helium.crpq.cnrs-nancy.fr/SARM/pages/roches.html). X-ray fluorescence (XRF) analyses for major and
159 trace elements were also obtained by the Laboratory of Sernageomin (Chile) in five soil
160 samples from the Puquío area. Platinum-group elements Ir and Pt were measured in
161 only one sample with the Nickel Sulphide Fire assay method and ICP-MS finish at
162 Geosciences Laboratories (Geo Labs, Sudbury, Canada). The elemental composition of
163 the glass was determined by electron microprobe analysis using a Cameca SX-100 at the
164 Centre de Microanalyse de Paris VI (CAMPARIS). To avoid loss of the most volatile
165 elements (Na and Cl in particular), we used a defocused beam of 10 μm diameter, an
166 accelerating voltage of 15 kV, and a beam current of 4 Na. Eleven samples were analyzed,
167 with 3 to 7 glass analyses per sample. The chemical data are reported in supplementary
168 dataset S1.

169 The water content was determined for glassy areas of 1mm in diameter on $\sim 500 \mu\text{m}$
170 thick double-polished sections using FTIR transmission microscopy with a VERTEX V70
171 spectrometer coupled to a Hyperion 3000 infrared microscope (IPAG Grenoble).
172 Infrared measurement were obtained in the $4000\text{-}1000 \text{ cm}^{-1}$ spectral range and water
173 contents were estimated by the intensity of the -OH fundamental stretching band at
174 3550 cm^{-1} (using a molar absorptivity coefficient of 67 L/mol , Stolper, 1982).

3.2 Petrography

The PGs are heterogeneous at the centimeter scale and contain variable amounts of pure glass (10 to 90%, average 50%) (Fig. 5) mixed with relict mineral grains (quartz, feldspars, pyroxenes being the most common), and scarce lithic fragments of volcanic origin. Dendritic crystals of Ca-pyroxene, wollastonite, plagioclase and less frequently melilite that formed during quenching of the glass are also common (Fig. 5d, e), locally associated with skeletal crystals of Ti-poor titanomagnetite. Iron sulphide grains (pyrrhotite or troilite) up to 100 μm are found adjacent to vesicles (Fig. 5b, f, g, h) but droplets of iron sulphides are also found in the glass (Supplementary Fig. S2). These iron sulphides, especially those within vesicles, often present a weathering pattern typically developed in hot desert climate (Supplementary Fig. S2b). Although the ratio of Fe/S determined by EDS analyses suggests a composition closer to pyrrhotite, their low or undetected magnetic signals suggest that these particles were antiferromagnetic troilite (FeS) grains before weathering. Some samples also contain droplets of Ni-free iron phosphide, generally in association with iron sulphide (Supplementary Fig. S2). EDS analyses indicate a composition close to Fe_3P . Within some glasses, we observed numerous droplets of native iron, iron sulphide, and iron phosphide. All sulphide particles are Ni-free. Rare metallic iron and iron carbides are also found.

The PGs contains numerous pyroxene crystallites. Relict grains of quartz within the silicate glass do not show evidence of melting. A few titanomagnetite grains show structures suggesting incipient melting and some pyroxene crystals show crystal overgrowth. Pristine zircon grains indicate that the temperature of decomposition of zircon to baddeleyite ($\sim 1775^\circ\text{C}$, El Goresy, 1965) was never reached.

The PGs exhibit several structures that could be interpreted as flow during melting (Fig. 2a). However, these structures are mostly common in samples that display well organized grooves on the surface and tubes suggesting that the putative flow structure is related to the melting of silicified plants.

3.3 Chemical composition

The bulk compositions of PG are in the range 59-64 wt% SiO₂, 10-15 wt% Al₂O₃, 4-13 wt% Na₂O, 4.7-6.5 wt% CaO, 3-4.5 wt% Fe₂O₃ (Supplementary dataset S1). At Puquio de Nuñez, the sandy soils (dominated by detrital quartz, plagioclase, K-feldspar, Ca-pyroxene, with accessory zircon, ilmenite, and titanomagnetite) present a slightly more elevated content of SiO₂ about 66 wt% than the PG. PG samples are enriched in either Na₂O or CaO with respect to the sandy soils. Regarding minor elements, the PGs are clearly depleted, for example in Zr, Pb and Ni compared to the soils. Sr concentrations are similar in soils and glasses (Supplementary Fig. S3 and supplementary dataset S1). Electron microprobe analyses of pure glass from all localities show an average composition similar to that of the whole rock Pica Glass samples (that also contains a significant and variable fraction of unmelted material), but significant inter-sample variations are observed: SiO₂ ranges from 58.5 to 70.7 wt%, and Al₂O₃ from 5.2 to 25.5 wt% Cl from 0.1 to 2.9 wt%. Bulk siderophile transition element contents are low (Ni < 20 ppm, Co < 12 ppm, Cu < 54 ppm) (Supplementary Fig. S3). The search for highly siderophile element enrichments (platinum-group elements) was unsuccessful (Ir < 0.02 ppb; Pt < 0.20 ppb). The water content in the glass was determined for 9 samples with 4 to 7 independent measurements. H₂O content is low (< average of 0.298 wt % ± 0.197) in all samples but one showing a large spread in 7 individual measurements from 0.160 wt% to 2.6 wt % (Table S1). The bulk composition of the silicified plants is at nearly 50 wt% SiO₂ and CaO 19 wt% (not corrected for the large loss on ignition due to the

presence of CO₂ and H₂O) with a notable total S content of 5.2%. SEM observations, however, suggest some late deposition of gypsum and calcium carbonates after the plants were silicified and burnt. The plants are depleted in most minor and trace elements except Sr compared to sands.

4. ¹⁴C dating

We obtained ¹⁴C ages from 11 samples of charcoal and organic matter from plant remains within the soils containing the PGs (Dataset S2). These ages, and those previously published (Blanco and Tomlinsson, 2013) for the PG-bearing areas (Table 1), correspond to the Pleistocene–Holocene transition (Fig. 6). A similar distribution of ¹⁴C ages was also reported (Nester et al., 2007; Gayo et al., 2012) for nearby locations to the south of our study area, which was interpreted as evidence for repeated expansions of riparian/wetland ecosystems, and perennial rivers along the southernmost Pampa del Tamarugal basin from 17.6–14.2 ka, 12.1–11.4 ka and from 1.01–0.71 ka (Gayo et al., 2012) (Supplementary Fig. S4).

All samples from the Puquio de Nuñez area display younger ¹⁴C ages than those observed at Quebrada de Chipana (Fig. 6). The two youngest ages were obtained on non-carbonized roots cutting the layer with carbonized plants, thus providing an upper limit for the age of the thermal event. The older ¹⁴C ages at Quebrada de Chipana can indicate either that the thermal event at Quebrada de Chipana is significantly older than the one at Puquio de Nuñez or that the ¹⁴C ages at Quebrada de Chipana represent ages of organic matter accumulated on the soil surface at least 2000 years prior to the thermal event.

Taking into account the extremely good preservation of organic matter in the Atacama Desert, these ¹⁴C ages can only provide a maximum age of the thermal event.

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250 **5. Paleomagnetism**

251 *5.1 Paleomagnetic Sampling and Methods*

252 At Puquio de Nuñez, standard 2.5 cm cores were drilled from unoriented blocks of PG. In
253 blocks with an approximately flat surface, cores were drilled orthogonally to this surface
254 interpreted as paleohorizontal at the time of PG formation. Fifteen glass samples, found
255 in the soil covered by a layer of sand in a position suggesting little or no displacement
256 after emplacement (Fig. 2e), were oriented with a molded horizontal plaster cap.

257 At Quebrada de Chipana, eight large blocks of 10 to 20 cm thick baked clays and three
258 PG blocks were oriented with a plaster cap. In addition, cores were drilled in 20 PG
259 blocks for which field observations suggested that these were practically *in situ* since the
260 time of formation. The samples were oriented with magnetic and sun compasses.
261 Samples from the red clays were then consolidated in the laboratory with sodium
262 silicate prior to further sub-sampling of standard one-inch diameter cores. Up to six
263 cores were drilled in each block. We also took several pieces of unoriented fragments of
264 the fine baked clay beds.

265 The remanent magnetizations were measured at Géosciences Rennes Laboratory with a
266 2G SQUID magnetometer and demagnetized thermally in a MMTD furnace or by
267 alternating field (AF) with the 2G online degausser. Thermomagnetic measurements
268 were performed with the Agico susceptibility meter KLY3 equipped with a CS3 furnace.
269 Hysteresis data were obtained on 1 to 3 mg whole rock samples with the AGM
270 magnetometer at LSCE (Gif/Yvette, France). First order reversal curve (FORC) diagrams
271 were processed with the FORCINEL software (Harrison and Feinberg, 2008).

272 Determination of the paleointensity of the Earth's magnetic field was attempted on 11 of
273 the baked clay samples and on 85 PG samples using the original Thellier and Thellier

(Thellier and Thellier, 1959; Chauvin et al., 2005) or the IZZI (Tauxe and Staudigel, 2004) procedure. For thermoremanent magnetization (TRM) acquisition, the samples were heated and cooled in air or in vacuum ($<10^{-2}$ mbar) under an applied dc field (Dataset S3) ranging from 30 to 50 μ T. Experiments were performed either on whole cores or on small fragments of unoriented samples that were fixed in a quartz tube using non-magnetic glass fibers and sodium silicate. A partial TRM check was performed every two temperature steps to check for heating induced mineralogical changes.

Archeomagnetic studies on bricks and ceramics have often shown a strong anisotropy of TRM. Thus, the magnetic anisotropy of the baked clays was determined with TRM acquisition in six positions (+x,-x,+y,-y,+z,-z). The cooling rate effect (Yu, 2011) on paleointensity determinations was tested only on the baked clays using a linear cooling rate of 0.3 °C/mn compared to the fastest cooling rate (>10 °C/mn) used for the routine paleointensity experiments.

5.2 Magnetic properties

Baked clay samples (Quebrada de Chipana) have the highest magnetic susceptibility and natural remanent magnetization (NRM) while the magnetic properties of the glasses at Puquio de Nuñez differ clearly from those at Quebrada de Chipana (Fig. 7).

PG samples with a large amount of glass at Puquio de Nuñez have the lowest NRM. The highest magnetic content of PG samples at Quebrada de Chipana is related to the highest content in relict grains and magnetite crystallites in the glass matrix. Samples from Quebrada de Guatacondo have a wide range of magnetic properties overlapping those of the Puquio de Nuñez and Quebrada de Chipana fields.

All samples of baked clays and silicate glasses record stable univectorial characteristic remanent magnetizations (ChRMs). Silicate glasses have a high stability upon AF

demagnetization with high medium destructive field values, allowing us to dismiss a possible lightning effect (Fig. 7).

The baked clays have two magnetic phases, one being magnetite and a higher coercivity phase carrying from 10 to 60% of the remanent magnetization not demagnetized above 100 mT (Fig. 7). The two phases are also recognized in hysteresis data (Fig. S5). This behavior is often observed in archeomagnetic studies on bricks. The high coercivity phase is common in bricks fired at high temperatures, and is likely due to the transformation of iron-rich clays at high temperatures. Distributed unblocking temperatures in the range 200-550°C is also a characteristic of archeomagnetic materials (Chauvin et al., 2000; McIntosh et al., 2011). We can conclude, therefore, that the baked soils in the present study have likely reached temperatures similar to those used to form archeological bricks (~700°C or above).

All glass samples show hysteresis cycles characteristic of magnetite, except one with saturation above 0.5T indicating a possible contribution from metallic iron (Supplementary Fig. S5). No evidence of pyrrhotite was found in thermomagnetic experiments. Further work is needed to decipher the contribution of iron sulphides to the magnetic signal.

5.3 Paleomagnetic directions

The baked clays at Quebrada de Chipana record well-clustered characteristic remanent magnetization (ChRM) directions (Fig. 8), except for one sample probably taken on a more disrupted part of the baked clay.

The direction of the PG at Quebrada de Chipana present some scatter because the blocks have likely been slightly disturbed since their formation but the mean ChRM direction determined from the glasses is indistinguishable from the one recorded by the baked clays (Table 2, Fig. 8).

ChRMs were determined for fifteen oriented samples at Puquio de Nuñez. The mean paleomagnetic direction recorded by the PG at Puquio de Nuñez is statistically different from the mean direction recorded by the baked clays or the PG at Quebrada de Chipana (Fig. 8). In order to further constrain the paleomagnetic test, we also determined the ChRM directions obtained from cores drilled perpendicular to nearly flat PG surface in 61 non oriented blocks found lying at the surface. Nine samples have a positive inclination at more than 45° from the mean direction. The mean inclination (angle to the surface) determined from the 52 unoriented blocks is -21.8° with an angle of confidence at 95% of 7.2° (Table 2). The nine samples yielding high positive inclinations were interpreted as overturned samples. If we invert the inclination for these samples, the mean inclination for the 61 samples is $-24.8^\circ \pm 6.7^\circ$. This mean inclination determined in the unoriented PG samples is in agreement with the inclination recorded by the oriented PG blocks.

At Quebrada de Guatacondo, the number of oriented cores is too low for a statistical comparison with the paleomagnetic result in the baked clays at Quebrada de Chipana.

5.4 Paleointensity experiments

Paleointensity determinations were attempted on 96 samples and 70 samples provided results with acceptable quality (Fig. 7, supplementary Fig. S6, Dataset S3). This high success rate is due to a NRM carried mainly by single domain grains of magnetite. The quality factor q is greater than 29 for more than 50% of the samples. PG samples with optical evidence of iron sulphides in the vesicles were the most affected by alteration during heating. This was easily characterized by the acquisition of a Chemical Remanent Magnetization in the direction of the applied field during the first step of the paleointensity experiment above ~300°C (Supplementary Fig. S6).

The baked clays provide very high quality paleointensity results with quality factors up to 150. The magnetic anisotropy correction is low. A cooling rate effect of 5 to 7% was observed in all samples except sample 13PI_P10a. These results are typical of those observed in archeological studies on bricks (Chauvin et al., 2000). It is difficult to estimate the natural cooling rate but cooling below 200°C is likely to occur within hours taking into account the thickness of the baked layer (20-40 cm). Thus the initial cooling rate is likely near the slowest cooling rate used in the laboratory.

The baked clays at Quebrada de Chipana give a well-defined paleointensity of 39.4 ± 1.6 μT after correction for anisotropy and cooling rate. The mean value from 18 determinations on PG samples from the Quebrada de Chipana locality is similar to the mean paleointensity determined for the baked clays (Fig. 8, Table 2).

The determination of the paleointensity was successful in 36 specimens at Puquio de Nuñez and most samples from the Puquio de Nuñez area provide significantly lower paleointensities than those observed in the baked clay samples of Quebrada Chipana (Fig. 8). Two groups of paleointensity values are observed. Twenty six determinations from 25 independent PG blocks provide a low field value of 20.9 ± 1.2 μT . The other group of 10 determinations, but from only three different blocks, provides a mean paleointensity value similar to the one at Quebrada de Chipana and at Quebrada de Guatacondo (Table 2).

The paleomagnetic directions and the paleointensity results are statistically different at Puquio de Nuñez and Quebrada de Chipana which are only separated by a few tens of km. This observation demonstrates that the thermal events at Puquio de Nuñez and Quebrada de Chipana did not occur under the same geomagnetic field configuration. The differences between the ChRM directions ($\sim 20^\circ$) and paleointensity results ($\sim 20\mu\text{T}$) at Puquio de Nuñez and Quebrada de Chipana are large enough to indicate the record of a

significant secular variation of the Earth's magnetic field. Such variations in inclination and intensity are only reasonable over a few centuries. For instance, such variations have occurred in Chile over the last three centuries (Roperch et al., 2015) that are characterized by very high rate of variations in magnetic inclination (up to $0.12^{\circ}/\text{yr}$) and in field intensity (up to $0.15\mu\text{T}/\text{yr}$). Altogether, the paleomagnetic data prove that the glasses at Quebrada Chipana and Puquio de Nuñez were formed at different times separated by at least a few hundred years.

5.6 Paleomagnetic test of a thermal event away from the glass fields

If the silicate glasses were formed during an airburst, evidence of thermal heating at high temperature should also be found elsewhere, i.e. away from the glass fields. About 200 m north of the Quebrada Chipana, at an elevation about 50 m above the silicate glass field, there is a meseta without glasses but with clasts of silicified limestone at the surface (Fig 3a). In view of the extremely low erosion rates in the Atacama Desert since the Miocene (Dunai et al., 2005), these clasts were likely already on the surface at the time of the formation of the PGs. We collected 15 unoriented clasts with sizes around 5 cm to test the hypothesis of a partial thermal remagnetization event. The samples were demagnetized in zero field and remagnetized in a field of $40\mu\text{T}$ as in the paleointensity experiments. The TRM acquired in the laboratory at 460°C are up to 10 times the intensity of the NRM. There is no paleomagnetic evidence for any thermal event having affected the clasts. Moreover, most samples showed profound color changes during heating above 400°C , indicating that they were not heated above this temperature since their formation. Overall, these experiments indicate that this surface, located only 200 m away from the glass fields, was never heated significantly.

6. Discussion

398 The areal extent of the Pica Glass and their composition are unlike any known historical
399 or prehistorical metallurgy slag deposit, precluding an anthropogenic origin. The
400 location (70 km west of the closest volcanic arc), the shape and size of the blocks, and
401 the mineralogy are inconsistent with a volcanic origin.

402 Glassy rocks, called fulgurites, can be formed in the subsoil by lightning in the form of
403 hollow tubes (Sponholz et al., 1993; Pasek et al., 2012). They are usually 1-2 cm in
404 diameter, with millimeter thick walls, but can in exceptional circumstances extends to
405 several meters depth and attain diameters of up to 15 cm. These characteristics strongly
406 contrast with the large areal distribution of the PG and with the occurrence of baked
407 soils over an area of 0.1 km². Heating of this thick baked layer or the formation of glasses
408 by lightning would imply an unrealistic number of lightning strikes on the same surface.
409 Moreover none of the PG and associated baked clay samples shows remagnetization by
410 strong fields (Fig. 7), which would be expected in case of successive adjacent lightning
411 strikes.

412 Another possible formation mechanism for surface glasses is a hypervelocity impact
413 (French and Koeberl, 2010). The PGs cannot be distal impact ejecta deposits because
414 such ejecta could not produce a 20 cm-thick layer of baked clays. We found no
415 geochemical evidence for contamination by an impacting body, with no enrichment in
416 metallic or platinoid elements in the glass. Textural evidence shows that iron sulphide
417 droplets were formed in situ mostly on the walls of gas vesicles (Fig. 5, Fig. S2).

418 The large spread of ¹⁴C ages and the different paleomagnetic fields (direction and
419 intensity) between localities Puquio de Nuñez and Quebrada de Chipana show that the
420 glasses were not formed synchronously at these sites, and thus cannot have formed
421 during a single thermal event triggered by a large airburst. Just as important is that we
422 were unable to find any evidence for a surface thermal event on the mesas immediately

423 adjacent to the specific low-elevation areas where glasses are found at Quebrada de
424 Chipana.

425 The only remaining viable hypothesis to account for the formation of PGs is akin to
426 pyrometamorphism during coal fires (Grapes, 2011; Stracher et al., 2011) or methane
427 flares forming paralavas (Grapes et al., 2013). The grooves on the surface of PG blocks
428 and tube-shape cavities found in many samples are remnants of melted silicified plants
429 and twigs. These plant remnants and imprints indicate that vegetation played a pivotal
430 role in the formation of the glasses. Cases of glass formation during fires of phytolith-
431 rich plants have been reported (Vélain, 1878; Baker and Baker, 1963). Vélain (1878)
432 made the first petrographic description of glasses found within ashes after haystack
433 fires in France. He clearly related the chemical composition of the glasses to the nature
434 and type of the burned hay or wheat, and pointed out that the extraterrestrial origin,
435 popularly attributed to these unusual glasses in the 19th century, was only the result of
436 superstition. Baker and Baker (1963) also made a detailed description of silica glass
437 formation during the burning of two large haystacks in Australia. Fusion and melting of
438 the opal phytoliths contained in the ~325 tons of pasture plants yielded about 16 tons of
439 silica glass (Baker and Baker, 1963).

440 The ¹⁴C ages of the plant remains further correlate with the timing of the two phases of
441 the Central Andean Pluvial Event (CAPE) (Fig. S5), a multi-millennial scale event of
442 increased rainfall in the high Andes (Quade et al., 2008), which are roughly coeval with
443 the two major periods of sea surface temperature drops in the north Atlantic (the so-
444 called Mystery Interval and the Younger Dryas) (Broecker et al., 2010). These two
445 periods also correspond for the most part to the maximum highstands of paleolake
446 Tauca nearly 100 m above the present-day surface of salars of Uyuni and Coipasa that
447 cover a large area of the southern Bolivian Altiplano (Fig. 1) (Sylvestre et al., 1999;

Plackzek et al., 2006; Blard et al., 2009; Gayo et al., 2012; Quesada et al., 2015). As precipitation in the high Andes increased discharge and elevated groundwater tables (Quade et al., 2008), large oases formed throughout the western Andean piedmont across the Atacama Desert (Rech et al., 2002, 2003, Saez et al., 2016). The present-day distribution of the glasses at Puquio de Nuñez roughly corresponds to an extensive paleowetland extending more than 3 km to the north of the present-day Puquio de Nuñez small oasis. Except for brief interludes of increased groundwater tables (2.5 – 1.7, 1.01 – 0.71 ka) most of the Holocene has been hyperarid in the Atacama (Gayo et al., 2012).

We thus propose that the PGs were produced *in situ* by fires in dry wetland soils rich in organic matter and siliceous plant remains (Pigati et al., 2014). Microscopic observations in thin section of apparent flow structures in samples displaying surface grooves suggest that the structures are likely remnants of melted elongated silicified plant materials. The water content in the glass is low (average of 0.298 wt % \pm 0.197, Table S1), but above the range of most impact glasses (Beran and Koeberl, 1997). Beran and Koeberl (1997) suggest that only very low H₂O contents in glasses (< 0.05 wt%) are diagnostic of an origin by impact. Microprobe analyses indicate high Cl values (up to 2.87 wt%) which have also been described from paralavas (Grapes et al., 2013). In some samples, the silicified remains were not always fully melted during burning of the organic matter.

The PG samples contain detrital relict grains within the glass and the whole-rock chemical composition of such glasses is intermediate between those of the desert sandy soil and the silicified plants. Soils with abundant organic matters and SiO₂-rich phytoliths, clay minerals and salts (sodium chloride, sodium and calcium sulfates,

472 carbonates, possible nitrates) may have melted at lower temperatures than needed to
473 melt detrital quartz grains.

474 Temperatures reached during natural fires are usually low at the soil surface (Stoof et al.,
475 2013) but may rapidly increase in cases of underground burning inside an organic
476 matter-rich layer beneath a sand lid as in the case of smoldering combustion during peat
477 fires (Rein et al., 2008). Very few examples of natural subsurface combustion leading to
478 soil fusion have been reported. Monod and Palausi (1961) first reported evidence of
479 melted rocks near Lake Faguibine (Mali) but this observation was later mistakenly
480 interpreted as incipient volcanism (El Abbas et al., 1993). However, Svensen et al.
481 (2003) demonstrated that subsurface combustion is the cause of heat and soil melting
482 and these authors suggest that the surface combustion in the Timbuktu region today
483 could be a frequent phenomenon in northern West Africa. Our observations at Pica
484 suggest that such fires, especially when very dry conditions facilitated the propagation
485 of the smoldering front (Prat-Guitart et al., 2016), may account for the formation of
486 similar irregular slag-like glassy rocks previously attributed to melting of surface
487 sediments during airbursts (Haines et al., 2001; Schultz et al., 2004; Osinski et al., 2008).
488 Indeed, the airburst hypothesis for the formation of surface glass mainly relies mostly
489 on numerical simulations (Wasson, 2003; Shuvalov and Trubetskaya, 2007; Boslough
490 and Crawford, 2008). As an example, the Dakhleh glass has been attributed to an
491 airburst (Osinski et al., 2008, Osinski et al., 2007) but evidence for this is sketchy
492 (Reimold and Koeberl, 2014). The Dakhleh glass shares numerous characteristics with
493 the PG. In particular they are confined around oases and show abundant imprints of
494 plants. The similar paleoenvironment at Pica and Dakhleh suggests that specific
495 paleogeographic conditions may be necessary to form this type of glasses. The
496 interpretation proposed for the Pica Glass may apply to the Dakhleh glass as well.

Similarly, several glass levels with morphological biosignatures such as phytoliths have been reported from Argentine Pampean glasses (Schultz et al., 2014) and interpreted as evidence for seven successive local impact events since the late Miocene. We suggest that these glasses may have also formed by successive *in situ* fires.

We propose that melting of soils and silica-rich plants during the burning of organic matter-rich layers does not require an external event like an airburst but could be caused by natural fires under specific paleoenvironmental conditions, such as strong climatic oscillations in arid regions. Self-ignition due to exothermal microbial decomposition has been proposed for other examples of peat-fires (Chateauneuf et al., 1986; Svensen et al., 2003) but humans could also have triggered these fires, and a late Pleistocene archaeological site (ca. 13-11 ka) is also known in the area (Latorre et al., 2013).

The two distinct periods of formation of the PGs refute any link with a single global worldwide catastrophic impact event, such as the one suggested to have triggered climate change at the onset of the Younger Dryas (Firestone et al., 2007; Bunch et al., 2012; and Wittke et al., 2013), a theory that is strongly debated (e.g., Pigati et al., 2012; Boslough et al., 2013; Holliday et al., 2014; Meltzer et al., 2014; van Hoesel et al., 2014).

The complex mineralogical assemblage found in the PG further demonstrates that the presence of iron sulphides, spherules of magnetite, iron droplets or iron phosphides do not necessarily indicate an impact event, as fire in a subsurface layer rich in organic matter may result in the formation of such exotic minerals by reduction of sulfates and iron oxides.

7. Conclusions

¹⁴C dating and paleomagnetism demonstrate that the studied silicate surface glasses from the Atacama Desert were formed at the end of the Pleistocene during at least two different thermal events separated by at least several hundred years.

The glasses are distributed across the surface of paleowetlands deposits. Melting of SiO₂-rich phytoliths and partially silicified plants was an important factor in the formation of these glasses. Extensive wetlands developed in the Atacama Desert during the latest Pleistocene due to an elevated groundwater table associated with the CAPE (an multi-millennial wet event roughly coeval with the Mystery interval and Younger Dryas) and the maximum highstands of paleolake Tauca in the Bolivian Altiplano. Organic matter accumulated from grasses and sedges in soils during these wet periods and subsequent dry periods triggered fires and smoldering combustion in the soil and plant litter with a very low moisture content. The strong climate oscillations during the Late Pleistocene would have provided such conditions for near-surface vitrification by fire.

Our results provide clues for revisiting other documented cases of unusual silicate glasses that in the past have been attributed to airbursts with implications for the determination of the rate of occurrence of such events on Earth (Boslough and Crawford, 2008), and the possible preservation of fossil life in impact glasses on planetary surfaces (Schultz et al., 2014).

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Figure captions.

Fig. 1. Satellite image (Google Earth) of the northern Atacama desert with locations of the Pica Glass fields: Puquio de Nuñez (PN), Quebrada de Chipana (QC), Quebrada de Guatacondo (QG) and NW of the town of Pica (NWP). Contour line spacing is 500 m. The Salars of Coipasa (SC) and Uyuni in the Bolivian Altiplano highlight the extent of the late Pleistocene paleolake Tauca.

Fig. 2. Field observations at Puquio de Nuñez. (a) Satellite image (Google Earth) showing locations where glasses were observed (yellow dots), ^{14}C ages and main paleomagnetic sampling (red stars). Elevation with contour line spacing of 10 m. The dashed thick black line indicates a tectonic flexure. (b, c) Field images showing outcrops with samples of dark glasses partially covering partially the ground. (d) Field photograph of a vitreous, dark green, vesiculated and irregularly shaped tabular PG on the surface. (e) Field photograph of a glass sample within the soil under a 5-10cm thick layer of sand.

Fig. 3. Field observations at Quebrada Chipana. (a) Distribution of silicate glasses and baked clays on a satellite image (Google Earth) with elevation contour line spacing of 10 m. Yellow dots indicate places where glasses and/or baked clays were observed. ^{14}C ages and paleomagnetic sampling (red stars) are shown on the map. Green polygon indicates the flat area with no trace of surface heating, located 50 m above the glass fields. (b, c) Field images of glasses in the westernmost area, (d, e) Silicate glasses overlying a 10 to 20 cm thick layer of red clays, (f) Field image of the layer of baked clays.

Fig. 4. Plant imprints in glasses. (a) Photograph showing PG overlying a ~20 cm thick layer of silicified plants at Quebrada de Chipana; (b) Silicified wetland plant remains (cf. Cyperaceae); (c) Photograph of a sample of glass overlying a layer of plants (Quebrada de Chipana locality); (d) Silicified twigs within a vitreous matrix; (e) SEM observation of a twig showing the replacement of the plant by silica. (f) Upper surface of one PG sample showing grooves due to plant imprints (Puquio de Nuñez locality); (g) Plant imprint within a glass sample from the NW Pica area.

Fig. 5. Microscope observations of glasses. (a) Transmitted light image of PG from PN with flow-like structure. (b) Reflected light image of iron sulphide (S) showing partial weathering-related oxidation (O). (c, d, e) Backscattered Electron (BSE) images of crystallite-rich glass with relict grains and dendritic overgrowths of feldspar and clinopyroxenes, typical of quench textures. (f) Iron sulphide grain nucleated on a vesicle. (g) Large sulphide grains in a vesicle. (h) Detrital grains in a glass matrix.

Fig. 6. ^{14}C age determinations. Calibrated ^{14}C age spectra (thick lines for median ages, different colors illustrate different samples, see Table 1). (a) 6 samples from Puquio de

Nuñez. (b) 9 samples from Quebrada de Chipana. (c) 2 samples from NW of Pica and Quebrada de Guatacondo. The Mystery Interval (MI) and the Younger Dryas (YD) cold periods at the end of the Pleistocene are highlighted with the yellow boxes while the two phases of Central Andean Pluvial Event (CAPE) (Gayo et al., 2012) are shown in green boxes

Fig. 7. Magnetic properties and examples of paleointensity results. (a) Plot of the magnetic susceptibility versus the intensity of the NRM showing significant magnetic variations between the PGs at Puquio de Nuñez and Quebrada de Chipana or within the Quebrada de Guatacondo glass field; (b, c) Variation of the intensity of the NRM during alternating field demagnetization for silicate glasses and baked clays; Paleointensity diagrams and associated orthogonal plots for a sample of baked clay (d), silicate glasses at Quebrada de Chipana (e) and Puquio de Nuñez (f and g). Red filled symbols correspond to points used to determine the slope of the best-fit line in the NRM-TRM plot. Triangles correspond to PTRM checks. For orthogonal plots, open green (filled red) symbols are projection in the vertical and horizontal plane, respectively.

Fig. 8. (a) Equal-area projections of the paleomagnetic directions determined in oriented samples at Puquio de Nuñez (open, filled symbols for respectively negative, positive inclinations. (b) Paleomagnetic directions at Quebrada de Chipana (glasses shown in green circles; baked clays with red diamonds). (c, d) Paleomagnetic inclinations at Puquio de Nuñez and Quebrada de Chipana. (e) Geomagnetic paleointensities determined in samples from Puquio de Nuñez and Quebrada de Chipana.

Dataset captions

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866 **Dataset S1.** Chemical data of major, minor and trace elements in glasses and sands.

867 Whole-rock chemical data for the Pica Glass were obtained by ICP-MS.

868 Only major elements are reported for microprobe data of pure glasses.

869 XRF determination for whole rock data for sands. The accuracy is assessed by

870 comparison with reference samples.

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872 Dataset S2. ^{14}C dating results obtained at “Plateforme Nationale LMC14”, Gif sur Yvette,

873 France

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876 **Dataset S3.** Paleointensity determinations in baked clays and glasses.

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878 **Dataset S4.** Google Earth KML file with additional information

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