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

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ABSTRACT

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

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. These events had no significant thermal effects on the ground. However, 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 have catastrophic effects (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 airburst 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 0.8 Ma) and northern Africa (Osinski et al., 2007, 2008) (Dakhleh glass, age 145 ± 19 ka). French and Koeberl (2010) point out that it is often difficult to ascribe 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

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Fig. 1. Satellite image (from 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 Salar de Coipasa (SC) and Salar de Uyuni in the Bolivian Altiplano highlight the extent of the late Pleistocene paleolake Tauca.

or disproving the impact origin of these glasses has implications for estimating the flux of airburst producing bolides to the Earth.

Massive glass blocks (called Pica Glass or PG in the following) 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 to complement ^{14}C dating, as it can be used to test the synchroneity of the glass formation at the different locations. Indeed the paleomagnetic study of the PG and underlying baked clays constrain the intensity and direction of the geomagnetic field at the time of glass formation. Moreover paleomagnetism also constrains the temperature reached by these clays. Finally it is also a test for the origin of the PG as fulgurites. Indeed, lighting 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 vol% vesicles) and irregularly shaped, tabular glassy bodies occur scattered on the surface of the Atacama desert 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 de Chipana, Quebrada de 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 (Figs. 2, 3). Their glassy texture demonstrates high temperature melting and quenching.

At the site called "Puquio de Nuñez", north of the small oasis of Puquio de Nuñez (Fig. 2a), the glasses are distributed over a ~2 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, grooves and tube-shaped cavities that are remnants of plants such as twigs and roots (Fig. 4; Supplementary Fig. S1).

Puquio de Nuñez oasis is presently mostly artificial (i.e. it has been dug out) and extends only for a few tens of meters. Water wells, drilled ~300 m to the east of Puquio de Nuñez, penetrate the water table located a few 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, glassy blocks of variable size up to 50 cm thick are scattered at the surface (Fig. 3b, c). To the east, glassy blocks 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 de 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 glass 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 glassy 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).

Abundant *in situ* glasses are found about 9 km to the northwest of the Pica town. 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 1100 m. Burnt soils without glasses are also observed on the surface in the same general area. Isolated glassy blocks also occur within the town of Pica itself, but these blocks could have been transported from their original location.

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

Whole-rock chemical analyses for 13 samples of PG, one sample of silicified plants and one soil sample were acquired at the