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Widespread glasses generated by cometary fireballs during the late Pleistocene in the Atacama Desert, Chile

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ABSTRACT

Twisted and folded silicate glasses (up to 50 cm across) concentrated in certain areas across the Atacama Desert near Pica (northern Chile) indicate nearly simultaneous (seconds to minutes) intense airbursts close to Earth's surface near the end of the Pleistocene. The evidence includes mineral decompositions that require ultrahigh temperatures, dynamic modes of emplacement for the glasses, and entrained meteoritic dust. Thousands of identical meteoritic grains trapped in these glasses show compositions and assemblages that resemble those found exclusively in comets and CI group primitive chondrites. Combined with the broad distribution of the glasses, the Pica glasses provide the first clear evidence for a cometary body (or bodies) exploding at a low altitude. This occurred soon after the arrival of proto-Archaic hunter-gatherers and around the time of rapid climate change in the Southern Hemisphere.

INTRODUCTION

Blanco et al. (2012) discovered late Pleistocene glassy slabs in the Atacama Desert in northern Chile along a 75 km north-south corridor, near and southward from the town of Pica. The glasses occur in five general areas (each 1–3 km^2) containing innumerable patches of folded and twisted masses, each covering 1 m^2 to over 100 m^2 (Fig. 1). Although initially attributed to near-surface bolides (Blanco et al., 2012; Perroud et al., 2016), a later study concluded that the Pica glasses resulted from intense grass fires (Roperch et al., 2017). New field studies and analyses of these glasses not only confirm the initial interpretation of a low-altitude airburst but also establish the nature of the bolide.

DESCRIPTION OF PICA GLASSES

Geologic Setting

The Pica glasses are found on top of a range of sedimentary facies (paleowetland and alluvial overbank deposits of Pleistocene age) resulting from the last period of glacial advances, with occasional distal glass clusters on older colluvium. The intermittent paleowetlands are related to groundwater-fed streams and oases once active during wet periods when increased rainfall at higher altitudes created groundwater recharge and large lakes in the Altiplano region of the Andes to the east (Placzek et al., 2006; Nester et al., 2007; Gayo et al., 2012). These wet periods resulted in grasses and flora, now largely lithified, and include the Sajsi (ca. ka), Tauca (15 ka), and Coipasa (ca. ka) paleolake highstand phases (Nester et al., 2007). The most recent phases are the last and most important and correlate with the Quebrada de Chipana (QC) and Puquio de Nuñez (PN) wetland deposits, respectively (Blanco et al., 2012; Roperch et al., 2017). A glacial re-advance (or stillstand) occurred at 12 ka (Alcálá-Reygosa, 2017), before the end of the Younger Dryas (YD) at 11.5 ka, coincident with a pulse of taxa (*Hippidion* [equines], *Glossotherium* [sloths], *Equus* [equines], *Mylodon* [ground sloth]) dropping out of the record (Barnosky and Lindsey, 2010). The glasses also formed at a time of particular interest due to some of the earliest known human settlements in northern Chile at 13–12 ka (Latorre et al., 2013), after humans arrived in Peru at 14.2–13.3 ka (Dillehay et al., 2012).

The PN glasses are typically concentrated on mounds and plateaus, which likely represent paleotopography, but they also occur in isolated clusters and over elongate strewn fields emerging from areas below active dunes between these mounds (Fig. S1 in the Supplemental Material[1]). Paleograsses and fossil flora are common in the paleowetland deposits created during wetter late Pleistocene conditions. At the QC locality, clusters of glass (typically 10–30 m across) are associated with mounds of clay emplaced on top of Pleistocene alluvium (Figs. S2 and S3). In certain areas, the glasses are mixed with clays emplaced on top of paleograsses developed on old terrace deposits associated with the Chipana ravine. The glasses at the Quebrada Guatacondo (QG) locality are more dispersed and mixed with silicified plant materials and clays. Scattered surface glasses also occur farther south, west of Quebrada Mani, and farther north near La Calera and Pica.

The highly vesicular glasses are characterized by their black/green color, along with evidence for folding and flowing while still partially molten but rapidly quenched (Fig. 2). Many have morphologies indicative of sliding, shearing, twisting, rolling, and folding (in some cases, more than twice) before being fully quenched (for further examples, see Figs. S4–S6). As a result, initially flat glassy slabs (5 cm to 7 cm thick) were transformed into large twisted fused masses (up to 50 cm across). The same glass characteristics (morphology, composition, and setting) at PN and QC characterize other occurrences to the south and north (Fig. 1).

Separate studies have reported calibrated ^{14}C ages on organic matter at four glass localities that range from ca. 16.3 cal. kyr B.P. to 12.1 cal. kyr B.P. (summarized in Roperch et al. [2017]), a range reflecting different ages of the wetland surface deposits. Burnt organic soil at PN directly below and in contact with the glass (Blanco

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[1]Supplemental Material. Further examples and discussion of the glasses, meteoritic components, possibly related distal material, and previous interpretations as products of grass fires. Please visit https://doi.org/10.1130/GEOL.S.16812856 to access the supplemental material, and contact editing@geosociety.org with any questions.

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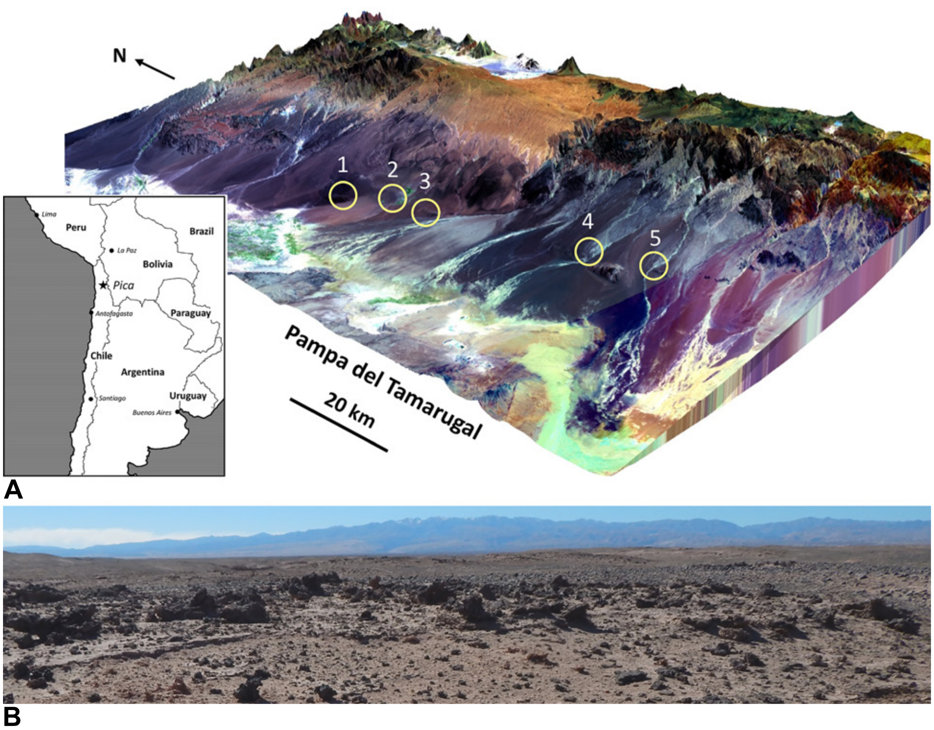

Figure 1. (A) Location map for glass localities in Chile: (1) southwest of La Calera; (2) near the town of Pica; (3) Puquio de Núñez (20°34.92′S, 69°21.77′W); (4) Quebrada de Chipana (20°54′S, 69°20.5′W); and (5) Quebrada Guatacondo (21°8.2′S; 69°36.9′W). (B) Concentration of glassy slabs (dark masses) at the Chipana locality. Largest example in this view is ~0.4 m across.

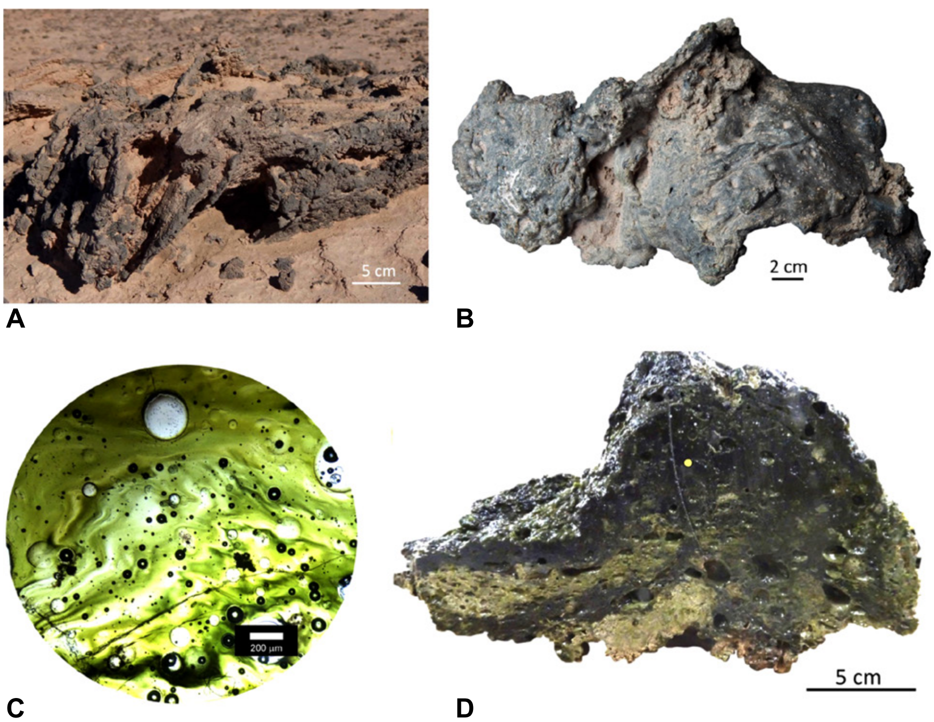

Figure 2. (A) Example of la arge glass slab at Chipana (Chile) that folded over during emplacement. (B) Twisted glass slab with two contrasting surfaces from Puquio de Núñez: one side is rough with sediments attached; the other side is smooth with flow patterns. Contrasting textures indicate formation on a sedimentary surface with subsequent mobilization. (C) Thin-section view of folded glass from Puquio de Núñez (Fig. 2D) showing typical green color, vesicles, and schlieren. (D) Cut section of large vesicular glass slab with multiple folds that indicate folding while still molten. Small yellow dot corresponds to the site of Figure 2C. These and other glasses contain signatures of extreme temperatures and numerous meteoritic fragments.

et al., 2012) sets a maximum age of 12.3 cal. kyr B.P. (−0.28/+0.29 cal. kyr B.P. at 95% confidence interval) for the glasses. Younger ages (11.5 and 11.1 cal. kyr B.P.) at PN came from noncarbonized roots that extended through a layer containing carbonized plants caused by the thermal event, and therefore postdating the glasses (Roperch et al., 2017). Glasses formed from older sediments at the QC site yielded ages (16.3 to 14.0 cal. kyr B.P.) that predate the thermal event by at least $\sim$2–4 k.y., consistent with the geologic setting. Consequently, the glasses formed between 12.3 and 11.5 cal. kyr B.P., a range constrained by the age of sediments from which they formed.

Compositions

We collected more than 300 representative glasses from the PN and QC sites (covering 1–3 km^2, separated by 30 km) as representative samples of each entire field, based on sample morphology and geologic setting. More than 70 polished thin sections were made from various-size glasses (8 samples from PN and 12 from QC) for microanalysis using a Hitachi SU-3500 variable-pressure scanning electron microscope. Chemical compositions of selected glasses were obtained using an EDAX Element energy-dispersive spectroscopy system (see the methods in the Supplemental Material), and results yielded the same heterogeneity reported by Roperch et al. (2017); consequently, they are not repeated here. Green schlieren-rich glasses from PN were microlite-poor and contained spherical, smooth-walled vesicles toward their tops. Similar textures were observed in some glasses from QC, but this site also included brownish glasses with abundant microlites, reflecting slower quench rates. Some zircons within the glasses (Fig. 3) had partially to completely decomposed to ZrO_2 (likely baddeleyite or other polymorphs) plus silica, indicative of temperatures $>$1670°C (Butterman and Foster, 1967) and often associated with terrestrial impacts (El Goresy, 1965; Wittmann et al., 2006).

Every sample examined thus far (70 thin sections) also contained thousands of exotic mineral grains and rock fragments (10 to $>$100 mineral grains and rock fragments per section) atypical of the local sediments. The observed minerals included euhedral Ni-troilite, buchwaldite (Fig. S10C), and Si-bearing chlorapatite that coat smooth vesicle walls (Figs. 4A and 4B); calcium-aluminum–rich inclusions (CAIs) (Figs. 4C and 4D); refractory Ca-Al-Ti–rich grains containing perovskite and corundum (Fig. 4E); and aqueously altered assemblages of Mg-rich silicates with troilite (for example, the serpentinite clast in Fig. 4F). The Ni-troilite (0.5–2 wt% Ni) is intergrown with Ni-free pyrrhotite and rimmed by cubanite ($CuFe_2S_3$) with submicron inclusions of pentlandite (Fig. 4B).

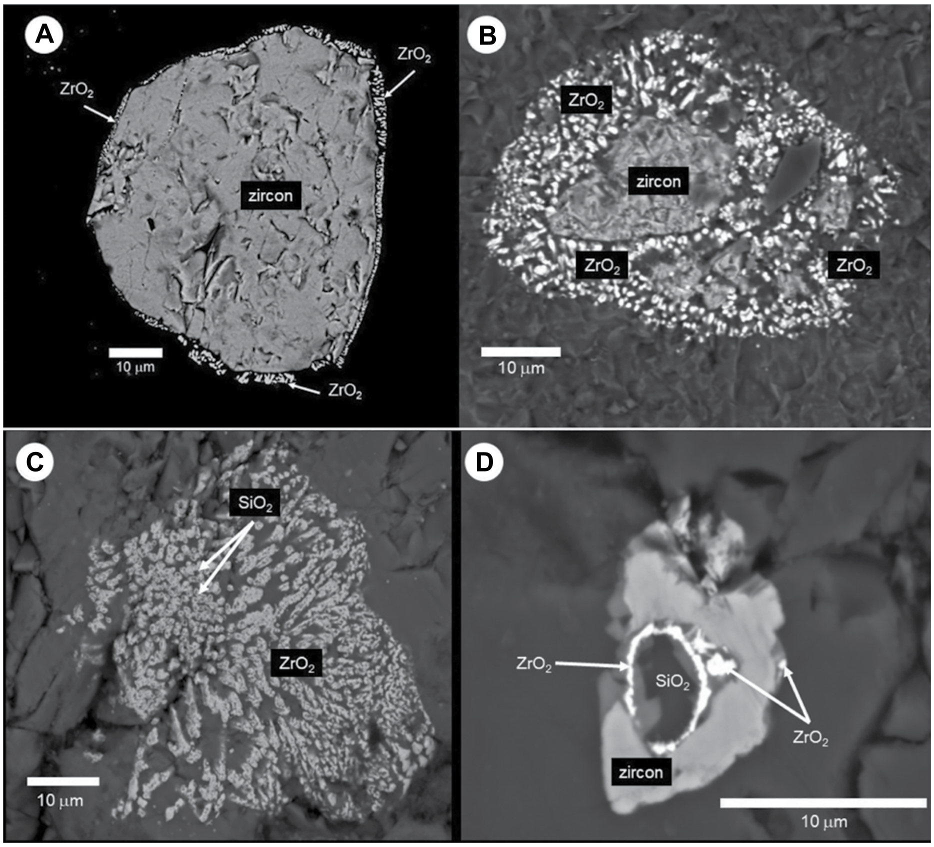

Figure 3. Backscattered-electron photomicrographs of zircon inclusions in Pica (Chile) impact glass. Zircon grains exhibit varying degrees of partial (A, B, D) to complete (C) decomposition from $ZrSiO_4$ to a ZrO_2 phase (possibly baddeleyite) and silica. Such thermal decomposition requires temperatures >1670°C with rapid quenching.

DISCUSSION AND INTERPRETATION

The morphology of the glasses (folded, sheared, and rolled) and thin-section views (internal flow patterns, elongated vesicles, entrained sediments) require a dynamic mode of emplacement yet could not have survived ballistic delivery from great distances without complete disruption. The glass composition and the entrained sediments indicate that they were derived from heating by high-intensity thermal radiation of a heterogeneous source, such as the overbank deposits, where there was insufficient time for mixing and homogenization of the melt. Paleograss imprints and H_2O diffusion fronts on the bottom of some *in situ* samples indicate emplacement on wet sediments before being completely quenched, consistent with local late Pleistocene environmental conditions at that time. Finally, all glasses occur in sediments of late Pleistocene age, with glasses at two sites 30 km apart having the same meteoritic components, including Ni-troilite. Consequently, we propose that all glasses were formed by one or several nearly simultaneous (seconds to hours apart) fireballs that fused surface sediments in at least five locations (each 1–3 km^2), rather than by grass fires (see the Supplemental Material).

Taken separately, the extraterrestrial clasts in the Pica glasses could represent a diverse assemblage of parent bodies, such as a rubble-pile asteroid. Taken together and viewed in light of both recent observations and modeling of CI meteorites (Berger et al., 2011) and Comet Wild-2 grains returned by NASA's Stardust mission (Berger et al., 2015), the Pica bolide was almost certainly a cometary body. For example, the cubanite overgrowths on troilite/pyrrhotite found in the Pica glasses are not only common in CI meteorites, but they were also found in Stardust samples from Comet 81P/Wild (Berger et al., 2011; Alfing et al., 2019) and have been demonstrated to be indicative of aqueous alteration on cometary bodies (Brownlee et al., 2012). Many of the assemblages in the Pica glasses consist of a melilite corona rimming dusty cores of sulfide-rich Ca-Al-Ti druse (sometimes containing carbonate, clays, and spinels; Figs. 4C and 4D) and thus appear similar to CAIs found in the Allende meteorite and other CV group meteorites. Although CAIs are exceedingly rare in CI meteorites, CAI materials have also been found in Stardust samples (Brownlee et al., 2012). Moreover, the perovskite with corundum is a super primordial refractory material (Fig. 4E), and the presence of serpentinite containing troilite (Fig. 4F) provides further evidence of an aqueously altered body (see the Supplemental Material).

Glass-Generation Process

There are two alternative hypotheses for the generation of glasses during an airburst event: (1) brief, intense radiant heat from the terminal explosion (e.g., Svetsov, 2006; Svetsov and Wasson, 2007); or (2) the same brief, intense radiant heat along with an added thermal contribution from heated gas and intense winds accompanying the downward momentum of the bolide, which would prolong the thermal event (Boslough and Crawford, 2008; Silber et al., 2018).

In the first model, the thickness of the melt layer is proportional to the thermal conductivity of the soil and the square root of time. Although large areas may be subjected to intense radiative heating, the low thermal conductivity and high opacity of most surface materials severely limit melting with depth (Svetsov and Wasson, 2007). As a result, only soils and melt glass with low absorption coefficients (e.g., clear quartz sand) could result in thick glassy slabs. The high absorption coefficients of surface sediments associated with the Pica glasses, however, would have limited the penetration depth of radiation from a bolide to only a few millimeters, especially over the brief exposure time from an airburst.

In the second model, supersonic winds continue downward and interact with the ground surface such that both radiation and convection play roles (Boslough and Crawford, 2008; Boslough, 2015). At the surface, both microturbulence and atmospheric vortices entrain and loft the fine, silty sands, thereby exposing these and underlying materials to radiation and resulting in further melting and amalgamation of melt packets. This process accounts for the dynamic emplacement textures (Fig. 2; Figs. S4 and S5) and collection of partially quenched melt packets into larger masses found in our study (Fig. S6).

There appears to be an absence of glass in regions well away from the paleowetlands, perhaps reflecting a contrasting response to the intense radiation from near-surface bolides. Clastic materials and larger rocks in the alluvium and lag deposits cover areas beyond the wetland deposits at QC and PN. In both settings, there is no apparent evidence for surface melting, except for ballistically transported glasses. The heat capacity of clasts and lag deposits, however, would have shielded underlying soils from transmitted radiant heat, especially due to the brief exposure of the event (tens of seconds). This absence might also reflect the contrasting response of powdery anhydrites that occur just below the lag surfaces. In contrast with shock or radiant heating of clays and silts, rapid vaporization of volatile-rich soils would have resulted in rapid melt disruption and dispersal of the melt droplets, rather than generation of large glassy slabs (Kieffer and Simonds, 1980).

The Pica glasses may be related to distal materials found in sediments of similar age much farther to the south at Quebrada del Chaco and Osorno in Patagonian Chile, 250 km and 2600 km

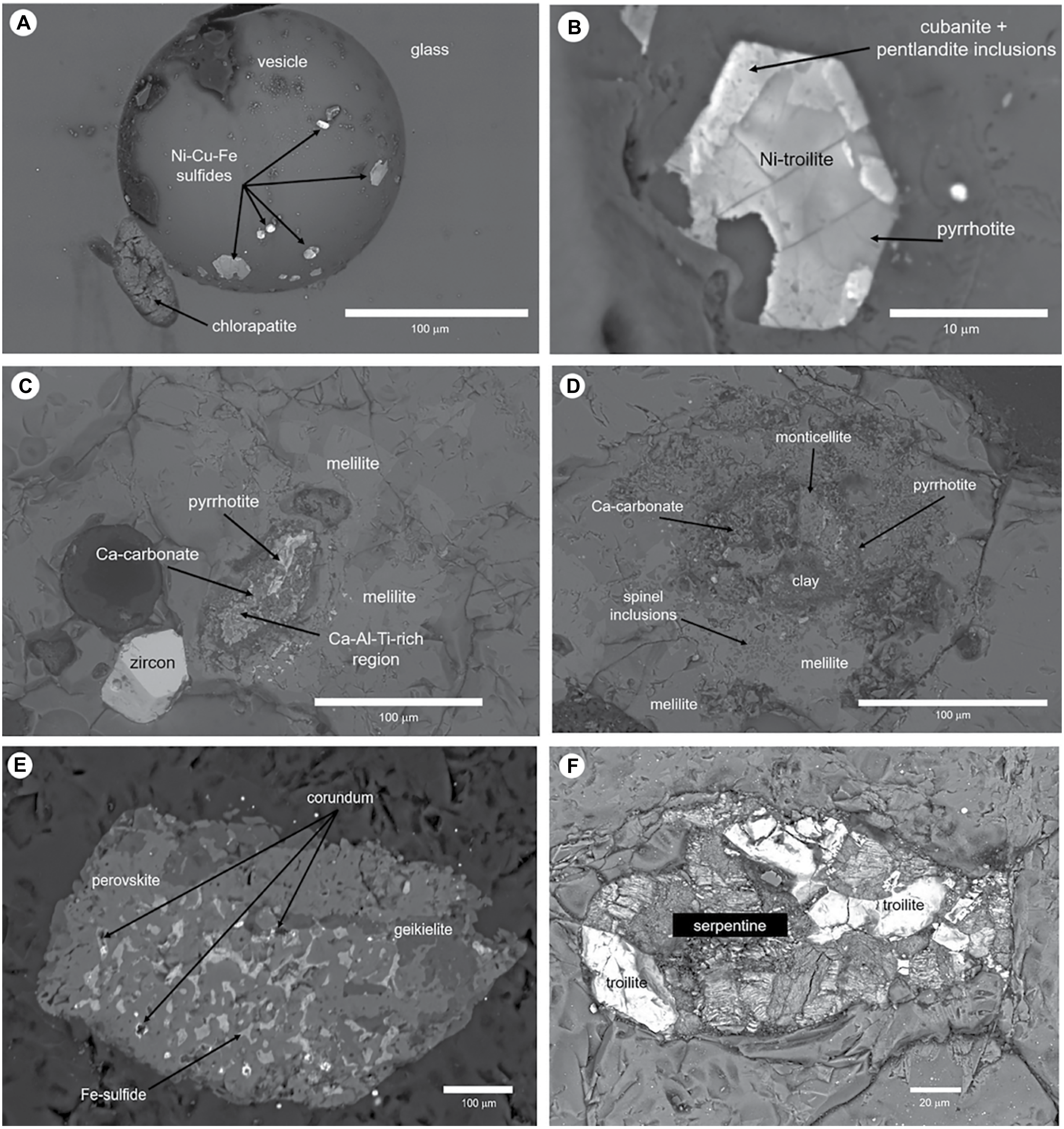

Figure 4. Backscattered-electron photomicrographs of extraterrestrial materials that occur abundantly in Pica (Chile) impact glass. (A) Euhedral platelets and laths of nickel-copper–rich iron sulfides occur often on the walls of vesicles. (B) Many of these sulfides are composed of Ni-bearing troilite and Ni-free pyrrhotite with Cu-Ni–rich overgrowths. (C,D) Altered calcium-aluminum–rich inclusions (CAIs) preserved in impact melt. (E) Ca-Al-Ti–rich refractory clast composed largely of intergrowths of perovskite ($CaTiO_3$) and geikielite ($MgTiO_3$). (F) Serpentinite clast (close to lizardite) containing troilite.

distance, respectively (see the Supplemental Material). The distribution and general similarity of glasses with the same entrained meteoritic clasts at widely separated locations require either successive low-altitude breakup of a single body with a low-angle trajectory or a series of tidally disrupted bodies entering the atmosphere at relatively high angles (>30° from the horizontal), analogous to the Shoemaker-Levy 9 collision by a fragmented cometary body on Jupiter.

Similar vesicular glassy slabs elsewhere (Australia and Egypt) have also been attributed to the effects of low-altitude bolides (e.g., Haines et al., 2001; Osinski et al., 2007). Although their origin has been questioned (e.g., Macdonald et al., 2004), these glasses also contain meteoritic microclasts supporting a similar origin (Harris and Schultz, 2020). The Pica glasses, however, are unique because of their very young age, abundance, widespread distribution, degree of preservation, and entrained clasts implicating a cometary bolide.

CONCLUSIONS

Our results have three important implications. First, the Pica glasses illustrate the difficulty in recognizing such events due to the poor geologic expression at the time of formation, the soil conditions necessary for glass generation, and the low preservation potential. Consequently, these glasses provide a unique, well-preserved recent record that can be used to constrain details about the formation process and the frequency of similar airbursts. Second, the dates for the Pica glasses coincide with the disappearance of Quaternary megafauna in South America, an extinction that was more severe than that on any other continent (Barnosky and Lindsey, 2010). While a direct causal link is not claimed, the timing is intriguing. Third, the entrained mineral assemblages are most consistent with a cometary body. Recent studies suggest that more than 16% of the objects >3 km in diameter hitting Earth may be cometary (Quintana and Schultz, 2019), which is higher than some previous estimates (e.g., Weissman, 2007). Such an airburst would affect a much broader area than a cratering event (for an equivalent-mass object), as demonstrated by the numerous airburst scours on Venus (e.g., Schultz, 1992) and entry models for Earth (Boslough, 2014).

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