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To cite this version:

P. Rochette, G. Di Vincenzo, J. Gattacceca, J.A. Barrat, B. Devouard, et al.. A two stage impact melting process in an impact glass strewn field from the Atacama Desert. Geochemical Perspectives Letters, 2024, 30, pp.28-33. 10.7185/geochemlet.2418. hal-04628661

HAL Id: hal-04628661
https://cnrs.hal.science/hal-04628661
Submitted on 30 Jun 2024

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A two stage impact melting process in an impact glass strewn field from the Atacama Desert

P. Rochette1*, G. Di Vincenzo2, J. Gattacceca1, J.A. Barrat3, B. Devouard1, L. Folco4, A. Musolino1, Y. Quesnel1

Abstract

A new type of silica-rich glass has been discovered associated with the known impact glass strewn field of the Atacama Desert. Based on petrography, chemical composition and indistinguishable 40Ar/39Ar formation ages at circa 6.6 Ma, we infer that these two glasses were produced by the same impact event, which gave rise to two successive compositionally different melt batches in close succession. The first one is a silica-rich melt derived from a mixture of quartz sand and weathered magmatic rocks. It is reduced and devoid of extraterrestrial contamination. The second one, much more abundant and which corresponds to the normal glass, is oxidised, highly contaminated by the iron type impactor and derived from an underlying unweathered dacitic rock. This scheme sheds a new light on the first second of the interaction between the Earth surface and a large metallic asteroid.

Introduction

Hypervelocity impacts on the Earth surface produce melts that can be ejected away from the crater (Glass and Simonson, 2013) at distance varying from 0.1 to less than 100 km for proximal ejecta or from 200 to 10,000 km for distal ejecta, such as tektites. Chemical and isotopic compositions of these melts may reflect provenance from the upper layers of the crust (Ma et al., 2004; Rochette et al., 2018), more or less contaminated by the extraterrestrial impactor (Koeberl, 2014), and showing variable compositions mimicking the heterogeneity of the target. Exploring the variabilities in the melt composition, target depth, and meteoritic contamination may help to understand details in the initial interactions between the impactor and the Earth surface. Such interactions have been already explored experimentally (Ebert et al., 2014), in proximal ejecta around small craters (Hamann et al. 2018; Folco et al., 2022), and in the largest ejecta known on Earth, the australasian tektite field (Folco et al., 2023).

We recently described an impact glass strewn field extending over 50 km along a N120° azimuth in the Atacama Desert (Gattacceca et al., 2021; Fig. 1). These black glasses, named atacamaites, are found as small splash-forms (average and maximum mass of 0.55 and 5.9 g, respectively), of dacitic composition. Their elemental and isotopic composition is compatible with an origin from local Andean magmatic rocks. The source crater has not been identified so far, but it was estimated to be relatively proximal (less than circa 100 km from the strewn field), based on the strong differences between atacamaites and bona fide tektites (see discussion in Gattacceca et al., 2021). In particular atacamaites show a relatively strong contamination by an iron meteorite impactor (likely IIAB type), on average 5 wt. % and up to 9 wt. %. They also contain a significant amount of magnetite, indicative of a large Fe3+/Fe tot ratio. The fission track dating method was used to obtain a preliminary late Miocene age estimate.

A distal NW satellite of the main strewn field (Fig. 1) was briefly reported in Gattacceca et al. (2021). In that distinct area, extending away for over 50 km, rare small glass teardrops are found. Because of their distinctive light brown colour and translucent lustre, pointing toward a different bulk composition than the normal black and opaque atacamaites, one may challenge the hypothesis that they derive from the same impact. Studying this different glass type, hereafter named silica-rich glass, and comparing it to the normal atacamaites is the purpose of the present contribution. Methods used are described in Supplementary Information.

This glass strewn field is quite unique in the terrestrial record by being intermediate between proximal and distal glass ejecta, suggesting it may bring original clues on the impact melting and ejecta processes.

Results and Interpretation

Field work and petrography. In the satellite strewn field, we collected while searching for meteorites 25 translucent glass samples labelled EM in the El Medano dense collection area (DCA; Hutzler et al., 2016), one sample in Caleta el Cobre DCA (labelled CEC) 25 km north of EM, and two samples 15 km southeast of...
EM. Median and maximum sample masses are 0.16 and 0.78 g, respectively. Magnetic susceptibilities (χ) values range from 43 to $87 \times 10^{-9}$ m$^3$/kg. If one excludes the three samples with masses well below 90 mg this range reduces to 69–80 $\times 10^{-9}$ m$^3$/kg, with a well-defined average of 76 ± 3 $\times 10^{-9}$ m$^3$/kg ($n = 25$). Electron probe microanalysis (EPMA) on six samples give similar values of SiO$_2$ and Na$_2$O + K$_2$O at 85.8 ± 0.7 and 0.32 ± 0.3 wt. %, respectively (Table S-1). Most samples have abraded teardrop shapes, but a few (the largest) are irregularly shaped with large bubbles (Fig. S-1). Optical and scanning electron microscopy of polished samples shows pervasive flow textures, vesicles and lechatelierite (i.e. pure silica glass) inclusions, often as twisted ribbons.

In the main strewn field systematic susceptibility measurements and an optical check of translucent character identified site K260 of Gattacceca et al. (2021) as rich in similar material: 53 samples, i.e. about 20 % of total samples of this site, have translucent character and $\chi < 85 \times 10^{-9}$ m$^3$/kg. The average $\chi$ of this population is 77 ± 4 $\times 10^{-9}$ m$^3$/kg. Twenty four other sampling sites from Gattacceca et al. (2021) possess one to four samples with the same features. Maximum and median masses of these silica-rich samples in the main strewn field are 2.3 and 0.21 g, respectively. In total, 99 silica-rich samples were identified in the main strewn field, i.e. about 1 % of the total collection.

One translucent sample from site K260 exhibits a higher susceptibility (169 $\times 10^{-9}$ m$^3$/kg), an anomaly attributable to a 1 mm large black spherical inclusion. A polished section through this inclusion shows a glass spherule typical of normal atacamaite material (i.e. enriched in Fe and Ni), embedded into silica-rich glass (Fig. S-1, Table S-1). This supports the idea that both glasses were welded within a hot spray.

Magnetic susceptibility measurements of the silica-rich glasses show values in agreement with the lack of magnetite and a purely paramagnetic susceptibility due to Fe$^{2+}$ only (see Rochette et al., 2015; Fig. S-2). The corresponding reduced character of this glass is further confirmed by a consistently negative loss on ignition (average −0.25 wt. %; Table S-2).

40Ar/39Ar dating. Three samples from the normal glass (samples K51, K48G, K326) and one (EM1a) from the silica-rich type were analysed by the 40Ar/39Ar dating method using both the laser step heating and the laser total fusion techniques. Details on the analytical procedure are given in the Supplementary Information. Uncertainties are given at 2 $\sigma$. Accuracy was checked by analysing fragments of moldavite VLTA2242 (Di Vincenzo, 2022). The full data set is listed in Table S-3.

Figure 1 Map of the normal atacamaite strewn field, surrounded by a solid black line, together with locations of the silica-rich glass. Large stars correspond to sites with the largest proportion of silica-rich samples.

Normal glass. All step heating experiments yielded reproducible flat or nearly flat age spectra, irrespective of the mass spectrometer utilised, with the exceptions of a few high temperature steps of data completed on samples K48G and K326 by the multi-collector noble gas mass spectrometer (Fig. S-3).
Concordant segments range from 65.3 to 100% of the total \(^{39}\text{Ar}\) released, with weighted mean dates indistinguishable within internal uncertainty, of 6.49 ± 0.20 to 6.60 ± 0.04 Ma (Fig. S-3). Data acquired using the multi-collector noble gas mass spectrometer yielded results with significantly lower analytical uncertainties and high temperature steps with apparent ages up to 6.7–7.0 Ma, suggestive of contamination by a minor extraneous Ar component (either excess or inherited Ar) heterogeneously distributed in the glass. Generally, total fusion data of single and a few glass fragments from the 0.35–0.50 mm grain fraction, in agreement with step heating data, gave mostly within sample concordant dates, ranging from 6.565 ± 0.028 to 6.605 ± 0.072 Ma (Fig. S-3). Combining intra-sample concordant \(^{40}\text{Ar}/^{39}\text{Ar}\) data from step heating and total fusion data yields a pooled mean age of 6.578 ± 0.011 Ma (±0.013 including all known sources of errors; Fig. 2).

Silica-rich glass. Step heating data yielded statistically concordant age spectra for two aliquots of sample EM1a, although with some internal scatter, yielding indistinguishable apparent ages for the two aliquots of ∼10 Ma (Fig. S-3). Analytical uncertainties are quite large when compared to \(^{40}\text{Ar}/^{39}\text{Ar}\) data of the normal glass, because of the low gas yield due to the very low K contents of the high silica glass. Total fusion data of a few fragments of the same sample reveal instead a more complex picture, with single runs yielding apparent ages spanning over a large time interval of 7 to 14 Ma (Fig. S-3) most likely due an extraneous Ar component heterogeneously distributed in the glass. In an \(^{36}\text{Ar}/^{40}\text{Ar}\) versus \(^{39}\text{Ar}/^{40}\text{Ar}\) isochron diagram (Fig. S-4), both step heating and total fusion data define a triangular envelope which requires at least three distinct Ar components: (1) atmospheric Ar, (2) a radiogenic Ar component, located along the ordinate and yielding a date of ∼6.5–7.0 Ma, and (3) extraneous Ar with a \(^{40}\text{Ar}/^{36}\text{Ar}\) ratio of ∼320. Selecting data points on the basis of their linearity and accepting linear regressions yielding a probability of fit ≥5 %, the triangular envelope defined by step heating data is defined toward the \(^{39}\text{Ar}/^{40}\text{Ar}\) axis by nineteen data points (Fig. S-4) that define a linear array (MSWD = 1.43) with an apparent intercept age of 7.1 ± 1.4 Ma.

Figure 2  Summary of \(^{40}\text{Ar}/^{39}\text{Ar}\) dates from step heating and total fusion data obtained in this study on normal glass (samples K48G, K326, K51) and a silica-rich glass (sample EM1a), through single and multi-collector mass spectrometers.

Figure 3 (a) Spidergram of trace elements normalised to primitive upper mantle (after McDonough and Sun, 1995) for the two glasses versus average coastal batholith data with SiO\(_2\) content close to the glass and a compatible isotopic ratio (see Fig. S-5); (b) ratio of average composition of silica-rich glass to the average composition of normal glass corrected from quartz addition. Alkali elements appear first, ordered by increasing ratio, then the other elements with increasing atomic weight.
atacamaites have patterns typical of the mainly dacitic local
et al.,
main strewn field. The six silica-rich samples are characterised
silica-rich samples were selected from the western satellite
envelope defined by total fusion data is defined toward the
0.69 Ma and a $^{40}$Ar/$^{36}$Ar 
array (MSWD $= 2020$) database, cut above SiO$_2$
strewn-field (24
and magmatic rocks from a two degree square centred on the main
63.7 ± 2.9 wt. % for normal atacamaites (Table S-2). Variability
ence is observed between samples from the satellite strewn field,
including the main strewn field samples. No significant differ-
ments. This points toward a rather homogeneous melt batch,
modelled normal atacamaite
Figure 3b. A strong deficit of alkali elements, especially for
Ni. We may thus propose that alkali depletion is due to the
dissolution of feldspars while Co and Ni depletion is due to
negligible extraterrestrial contamination in the silica-rich glass
compared to the normal glass (see discussion in Supplementary Information). Regarding the other enriched ele-
ments, those enriched by a factor of more than 2 are Sc, Ti, Cr, Mn, Zr, Nb, Hf, Ta. This may be explained by addition of sand heavy minerals such as chromite and zircon. To summarise, the silica-rich glass could be derived by melting a weathered dacitic target of similar composition as normal atacamaitae, together with quartz sand and heavy minerals.

This interpretation can be confronted with the iso-
topic compositions of Sr and Nd (Fig. 4, Table S-5). With an
$^{87}$Sr/$^{86}$Sr value of 0.713 for K260 sample and an average of
0.719 for the three samples from the satellite strewn field, the
silica-rich glass is more radiogenic than the normal glass that has an $^{87}$Sr/$^{86}$Sr ratio <0.708. Most local rocks have $^{87}$Sr/$^{86}$Sr below 0.710, and the ones with ratios higher than 0.718 are silica-rich. The Nd isotopic ratio also shows a distinct signature for the two glasses. The isotopic data thus invalidate the simple model based on element data alone, and indicate that the mag-
matic component in the silica-rich glass does not have the same isotopic signature as the source of normal atacamaitae.

Discussion and Conclusions

Based on indistinguishable formation ages within uncertainties, on the geochemical constraints, on the observation that both normal glass and high silica glass coexist within a single sample and the fact that chemically identical silica-rich glasses are present in both the main and the satellite strewn fields, a single impact event seems to be the most likely hypothesis. In addition, the alternative hypothesis that the two glass types were generated by two independent impacts seems to be an unlikely possi-
bility based on a probabilistic basis. Indeed, following the model proposed by Rochette et al. (2023), one can compute the probability that a second impact occurred within a maximum 0.9 Ma time window (based on the uncertainties of $^{40}$Ar/$^{39}$Ar ages) and within 100 km distance from the one producing the normal atacamaitae. This probability is 0.4 % for a crater >1 km diameter.

Therefore, we can put forward a scenario of impact melt-
ing of the Atacama Desert surface in two stages (Fig. S-6). In the first stage, the upper metres of the target, consisting of aeolian sands and weathered regolith derived from magmatic materials (e.g., tephra or transported detritus), is melted and reduced without significant impactor contamination, and ejected toward both the western satellite and the main strewn fields. Fractions of a second later an underlying unweathered dacitic rock is melted in greater quantity, mixed variably with the oxidised sprayed impactor, and ejected only in the main strewn field, i.e. over a shorter distance than the first batch (about 50 km less). Surface regolith cannot simply derive from the underlying dacite as isotopic data and trace element patterns do not match, but it may derive from a mixture of late tephra and/or degradation of transported local rocks. Another type of scenario is a lateral chemical and/or lithological contrast within the melted surface, e.g., made of a fresh dacitic outcrop surrounded by a regolith, with synchronous melting. However, we favour the vertical layering scenario based on the principle of Occam’s razor and the fact that the lateral contrast scenario does not provide a logical sequential scenario for the impactor contamination contrast. In our scenario the first melt, heated by radiating compressed air, is not interacting with the impactor spray. This sce-
nario, compatible with theoretical impact modelling (Artemieva, 2002; Wakita et al., 2022; Carlson et al., 2023), also implies that the first melt batch was ejected farther than the more abundant second one. As a consequence, it is expected that the source...
crater should be located closer to the main strewn field. The source crater is tentatively located along the apparent ejecta lobe oriented N120°, East of the main strewn field (Fig. 1). Geochemically distinct types of ballistically ejected impact glasses linked to a single impact event have been described in the literature, such as around the Zhamanshin and Kamil craters (Jonasova et al., 2016; Fazio et al., 2016). However, the 100 km wide atacamaite strewn field is a rather unique example where the kinematics of impactor-target interaction can be traced with such detail. The second largest comparable case, the Darwin 50 km wide strewn field, does show chemical variability but not with such a dichotomy in particular in impactor contamination and redox state (Howard, 2008). The origin of the reduction observed in the silica-rich glass remains a puzzle: one could invoke biomass carbon, as advocated for the fire derived Pica glass in northern Atacama (Roperch et al., 2017) and the Darwin glass (Howard et al., 2013). The Libyan Desert glass strewn field is larger than the atacamaite one, but its extension is suspected to be related to fluvial transport (Jimenez-Martinez et al., 2015) and it shows no evidence of ballistic transport. It is therefore not a relevant comparison.

Acknowledgements

The Ar laser probe facility was realised with the financial support of CNR. We acknowledge R. Romero, who provided eight more Si-rich samples, as well as the input of one anonymous reviewer, K. Howard and Journal editor that helped improving our manuscript. Work partly supported by the ANR ET-Megafire project (ANR-21-CE49-0014-03).

Editor: Romain Tartise

Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2418.

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References

Di Vincenzo, G. (2022) High precision multi-collector 40Ar39Ar dating of mola
dites (Central European tektites) reconciles geochronological and paleo-
chemgeo.2022.121026

.gca.2023.09.018
00140-4
