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- Discovery of a $\sim 650 \text{ km}^2$ impact glass strewnfield in the Central Depression of the Atacama Desert
- cm-sized splash-form glassy objects, called atacamaites, formed by impact at $7.8 \pm 0.26 \text{ Ma}$
- Dacitic composition with the addition of a variable iron meteorite contamination, 5 wt.% on average
- Small size, heterogeneity, oxidation state, contamination level distinguish them from tektites
- Impactor was an iron meteoroid, very likely from the IIAB group

A 650 km² Miocene strewnfield of splash-form impact glasses
in the Atacama Desert, Chile.

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ABSTRACT

Glassy ejecta are associated to a limited number of impact craters, and yet hold key information about hypervelocity impact processes. Here we report on the discovery of a ~650 km² impact glass strewnfield in the Central Depression of the Atacama Desert. These cm-sized splash-form objects, that we refer to as atacamaites, are essentially composed of a dacitic glass formed by high-temperature melting of local magmatic rocks, with the addition of a variable iron meteorite contamination, 5 wt.% on average. The most likely nature for the impactor is the IIAB iron group. The fission-track plateau method, on two samples, yielded a mean formation age of 7.83±0.26 Ma. No associated impact crater has been discovered so far, suggesting it may be a relatively small, km-sized crater. The glassy nature, aerodynamic shapes, elevated formation temperature, and low water content are reminiscent of tektites. However, their small size, heterogeneity, oxidation state, significant contamination by the impactor, and likely more proximal provenance distinguish them from tektites. Atacamaites have no equivalent among the few known terrestrial ejected impact glasses, and increase the intriguing diversity of such products that we propose to name “tektoids”.

1. Introduction

Natural silicate glasses generated by hypervelocity impact encompass melts in breccia, and impact glasses *per se*, i.e., individual pieces of glasses with minor proportions of relict unmolten grains or quenched crystals (Dressler and Reimold, 2001; Glass and Simonson, 2013; Koeberl, 2014). Tektites are nearly pure impact glasses ballistically ejected at long distance from their source, and bear typical splash-form shapes. Presently, five tektite strewnfields are recognized (Table 1). Beside tektites, more proximal splash-form impact glasses are found associated with a small number of craters (Table 1). The formation of tektites and other ejected

impact glasses remains largely enigmatic, partly due to their small number of occurrences and variable characteristics. Here we report on the discovery of impact glasses from the Atacama Desert (referred to as “atacamaites”).

2. Geological setting, strewnfield, macroscopic description

The atacamaite strewnfield is located in the Central Depression of the Atacama Desert between the Coastal Cordillera to the west and the Precordillera (Cordillera Domeyko) to the east. Local rocks are Middle Jurassic to Lower Eocene calc-alkaline volcanic and intrusive rocks present as rocky reliefs and smooth landforms, partly covered unconformably by a thin layer of Upper Miocene-Pliocene alluvial deposits consisting in unconsolidated polymict gravels supported by a sandy matrix deposited between 10 Ma and 1 Ma (Espinoza et al., 2012).

Centimeter-sized dark glassy stones were first noticed in 2011 by one us (MW). Subsequent dedicated field work allowed collecting ~23,000 samples¹ from over 100 discrete locations over a surface of ~650 km² (Fig. 1). The borders of the strewnfield are constrained by sites where a 60 man.minutes search did not reveal a single atacamaite. A few tens of similar-looking glass samples have been found sporadically about 40 km northwest of the strewnfield. The maximum dimension of the strewnfield is therefore at least 100 km. Samples were encountered lying on the desert surface, and more abundant, up to several tens per m², in gravels concentrations. They were encountered on all geological units present in the area. They range from 1 to 35 mm in length, with an average mass of 0.55 ± 0.48 g (1σ), and a maximum mass of 5.9 g. They are pieces of black glass, with minor vesicularity. The vast majority of samples display globular forms, with rare button, dumbbell, or teardrop shapes (Fig. 2A). The average shape parameters L (longest over intermediate axes) and F (intermediate over short axes) are

¹ Research material is available upon request to the first author

1.74±0.57 and 1.43±0.30 (n=989). Most pieces show a somewhat dull abraded surface attributed to transport and/or sand blasting. A limited number of samples show a shiny surface with small droplets stuck to the surface, as well as contorted splash-forms.

3. Methods

Optical microscopy was performed with a Leica DM2500P petrographic microscope at CEREGE, France. Backscattered electron (BSE) images, microanalyses by energy dispersive spectroscopy (EDS) and chemical maps were acquired with a Hitachi S3000-N Scanning Electron Microscope (SEM) operated at 15 kV and equipped with a Bruker X-ray XFlash detector and a Spirit analyzer at CEREGE. Semi-quantitative analyses used a variety of natural and synthetic standards.

The grain density was measured with a Quantachrome helium stereopycnometer at CEREGE. Magnetic susceptibility was measured with an Agico MFK1 susceptibility at CEREGE.

Whole-rock major, trace elements and isotopic compositions were determined at the PSO/IUEM (Pôle Spectrométrie Océan, Institut Universitaire Européen de la Mer, Brest, France). 100-150 mg of atacamaite were digested on a hot plate heated to 125°C, using sequential mixtures of HF/HNO₃, HNO₃ and HCl. The aliquots of the obtained solutions were used for the determination of major and trace element concentrations, Sr and Nd isotopic compositions. Major elements, Ni and Co abundances were analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AES) using a Horiba Jobin Yvon Ultima spectrometer and following the analytical procedure of Cotten et al. (1995). Relative standard deviations are < 2%. The accuracy is better than 7% for Na and P, and much better than 3% for the other elements. Trace element concentrations were measured with a Thermo® Element2 ICP-SFMS (inductively coupled plasma-sector field mass spectrometer). Concentrations were determined following the procedure described by Barrat et al. (2012, 2016). Based on results obtained on many standards, the reproducibility and accuracy are always better than 5%. Strontium and Nd fractions were prepared following conventional ion exchange techniques. They were analyzed using a Thermo® Triton TIMS (thermal ionization mass spectrometer). Isotopic ratios were normalized against ⁸⁶Sr/⁸⁸Sr = 0.1194 and ¹⁴⁶Nd/¹⁴⁴Nd=0.7219. The values

obtained for NBS 987 and La Jolla standards during the course of the study are respectively $^{87}\text{Sr}/^{86}\text{Sr} = 0.710254 \pm 0.000003$ (2σ , $n=8$) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.511830 \pm 0.000003$ (2σ , $n=6$).

Quantitative major element analyses were conducted using electron microprobe analyses (EPMA) Cameca SX100 at UPMC CAMPARIS facility. The operating conditions were 15 kV accelerating voltage with a current of 10 nA and a counting time of 30 s, with a focused beam (1 μm). Both natural and synthetic standards were used for calibration: albite for Na; anorthite for Al; apatite for P; diopside for Mg, Si, Ca; orthoclase for K; MnTiO_3 for Mn and Ti; Fe_2O_3 for Fe; and NiO for Ni. Typical detection limits are (in ppm): 450 for Na, 470 for Al, 710 for Mg, 670 for Si, 610 for Ca, 600 for K, 1040 for Mn, 420 for Ti, 1270 for Fe, and 1330 for Ni.

^{57}Fe Mössbauer spectroscopy (^{57}Fe -MS) was conducted at CBPF, Brazil. It was performed at room temperature (RT) in standard transmission geometry using a 25 mCi $^{57}\text{Co}/\text{Rh}$ radioactive source in sinusoidal mode. Spectra were recorded for 96 hours in a 512 channels spectrometer and the drive velocity calibration was taken at room temperature (RT) with an α -Fe foil. All isomer shifts reported in this work are given relative to α -Fe at RT. The error in source velocity is less than 1%. For each studied sample, about 100 mg of material was grinded and used as Mössbauer absorber. Spectral analysis was performed with the two-dimensional extended Voigt-based fitting method (x-VBF) developed by Lagarec and Rancourt (1997). This method provides the total Probability Density Distribution (PDD) of static hyperfine parameters allowing the analysis of independent, partially or fully correlated arbitrary-shape partial distributions of isomer shift (δ), quadrupole splitting (Δ) and, for magnetically ordered materials, hyperfine magnetic Zeeman splitting (z).

Micro-infrared spectroscopy was performed using a Bruker Hyperion Microscope coupled with a Vertex 70 FTIR (Fourier-transform infrared spectroscopy) spectrometer at the Institut de Planétologie et d'Astrophysique de Grenoble, France. Double polished sections of atacamite were prepared with thicknesses in the 300-600 μm range. Transmission spectra were obtained using 32 scans at a spectral resolution of 4 cm^{-1} for areas of typical size 100 μm x 100 μm . The absorbance due to H_2O in the glasses was measured at 3570 cm^{-1} and the water contents were estimated using a Molar Absorptivity of 74.8 $\text{L}/(\text{mol}\cdot\text{cm})$ (Beran and Koeberl, 1997) and a density of 2430 kg/m^3 (as measured by helium pycnometry, see below).

Raman spectra of SiO_2 rich inclusions were obtained at Laboratoire de Géologie de Lyon (ENS Lyon, France) using a LabRAM HR800 Evolution spectrometer with a confocal Czerny-Turner geometry and a laser source of 532 nm in wavelength. Spectra were acquired using a

laser power of 10 mW, and 25 accumulations of 5 to 15s. Gratings with 600 groove/mm were used to cover the frequency range 60 to 1300 cm⁻¹.

Fission-tracks ages were obtained following the protocol established at the Institute of Geosciences and Earth Resources (IGG-CNR) of Pisa (Laurenzi et al., 2007): samples JG26 and PT7E were handmade crushed to reduced them in multiple pieces. A fraction of each sample was irradiated in the Lazy Susan (Cd ratio 6.5 for Au and 48 for Co) facility of the Triga Mark II reactor of LENA, University of Pavia (Italy). After irradiation, fractions for spontaneous and induced track counting were mounted in epoxy resin, polished, and etched for track revelation (120s in 20% HF at 40°C). Tracks were counted under a Jena-Jenaval microscope with a magnification of 500x. Track-diameters in glass were measured with a magnification of 1000x with a digital tablet. We corrected the obtained ages for track annealing (i.e., track shortening) that occurs even at ambient temperature, and that is revealed by a spontaneous to induced track-diameter ratio $D_s/D_I < 1$ (Storzer and Wagner, 1969). Spontaneous track sizes are reduced by ~ 30 % in JG26 and ~ 20 % in PT7E (Table 4). The correction follows the plateau method which consists in re-establishing, through laboratory thermal treatments, identical etching efficiencies for spontaneous and induced tracks (Storzer and Poupeau, 1973). In this study, following the common practice, only one heating step (4h at 220°C) was used (e.g., Sandhu et al., 1993).

3. Petrography

Atacamaite are entirely glassy in the vast majority of cases. They contain a variable proportion (few vol.%) of vesicles ca. 100 µm in diameter. Complex schlieren textures are observed (Figure 2B). Some samples have texture suggesting formation by accretion of molten beads of a few hundreds µm in size (Fig. 2a, Fig. 2c). Lechatelierite (nearly pure silica glass), identified in particular by Raman spectroscopy (Fig. S1), is present as small patches with size ranging from a few µm to more than 2 mm. Some have a whirling texture indicating strong deformation in liquid state (Fig. 2D).

In the most magnetic samples, iron oxides can be observed as dendritic assemblages of micrometer-sized crystallites forming threads or globules (Fig. 2E). These iron oxides were observed only in samples with magnetic susceptibility higher than $\sim 350 \times 10^{-9} \text{ m}^3/\text{kg}$, which make up 10% of our collection. A few relict grains of incompletely molten quartz were observed in rare samples that were selected among several hundreds because of their abnormal, highly vesicular aspect.

The grain density, measured by helium pycnometry on three separate atacamaite batches totaling 67 g, is 2.48 g/cm^3 . The water content estimated by micro infrared spectroscopy is $177 \pm 32 \text{ ppm}$ (19 analyses, on 4 samples).

4. Geochemistry

Magnetic susceptibility of atacamaites shows a log normal distribution with a median of $10^{-9} \text{ m}^3/\text{kg}$ compatible with a paramagnetic behavior, i.e., iron diluted in the glass (Rochette et al., 2015). Magnetic susceptibility correlates roughly with the bulk Ni content, indicating that it may be a good proxy to select samples with higher extraterrestrial contamination (Rochette et al., 2015). Therefore, in addition to regular samples, we selected specifically samples with high susceptibility (above $300 \times 10^{-9} \text{ m}^3/\text{kg}$, and up to $3593 \times 10^{-9} \text{ m}^3/\text{kg}$) for bulk major and trace elements analyses, and EPMA.

Average bulk chemical composition of atacamaites (Table 2) is similar to a K-rich dacite, with $\text{SiO}_2 = 64.1 \text{ wt.}\%$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.54 \text{ wt.}\%$, and $\text{K}_2\text{O} = 2.98 \text{ wt.}\%$ ($n=15$). Iron is extremely heterogeneous ($\text{FeO}_{\text{total}}$ ranges from 4.58 to 14.2 wt.%), and correlates with Ni and Co abundances that are high, up to 4800 ppm and 400 ppm, respectively (Fig. 3). At microscopic scale, EPMA (Table S1) show that the Fe-rich regions are also enriched in Ni, with a good correlation between Ni and Fe contents (Fig. 3a).

Chondrite-normalized REE patterns are similar for all samples, characterized by a $\text{La}_\text{N}/\text{Lu}_\text{N}$ ratio ranging from 7.47 to 8.00 and a significant negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.50$), compatible with a dacitic target (Fig. 4). Strontium and Nd isotopic compositions, measured for five samples, also reveal fairly homogeneous isotopic compositions, with $^{87}\text{Sr}/^{86}\text{Sr} = 0.7076 \pm 0.0001$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512636 \pm 0.000006$ (Fig. 5).

5. Mössbauer spectroscopy

Five atacamaite samples were studied for Mössbauer spectroscopy. The room temperature ^{57}Fe Mössbauer spectra of all samples were fitted with two components described as distribution 1 (D1) and distribution 2 (D2). A typical spectrum is shown in Figure 6a. Only sample J338-23, selected for its high magnetic susceptibility, exhibited a magnetic phase ordered at room temperature, identified as magnetite and fitted with two sextets assigned as Fe-A and Fe-B. The former, with average hyperfine field (B_hf) ~ 49 T, corresponds to Fe^{3+} at tetrahedral sites in magnetite while the latter ($B_\text{hf} \sim 45$ T) to $\text{Fe}^{2.5+}$ at octahedral sites (Cornell and Schwertmann 2003).

Despite the differences in relative areas, all samples exhibit similar average hyperfine parameters for D1 and D2 (Table 3). The main distribution D1 presents average isomer shift $\langle\delta\rangle \sim 0.88 - 1.02$ mm/s and average quadrupole splitting $\langle\Delta\rangle \sim 1.95 - 2.19$ mm/s that is usually associated to Fe^{2+} in octahedral coordination, as shown in previous works on tektites and other natural glasses (Dunlap and Sibley 2004; Stewart et al. 2003). However, as pointed out by Rossano et al. (1999), D1 could also be assigned to a five-fold co-ordinated Fe^{2+} . In contrast, distribution D2 with $\langle\delta\rangle \sim 0.49 - 0.56$ mm/s and $\langle\Delta\rangle \sim 0.76 - 0.83$ mm/s is more likely to be Fe^{3+} in octahedral coordination (Johnson and Johnson 2005). Although previous works on tektites (e.g., Australasian) indicate $\langle\Delta\rangle \sim 0.00$ mm/s for Fe^{3+} (Dunlap and Sibley

2004), some impact glasses (e.g., Aouelloul glass, irghizites) show iron species with appreciable quadrupole splitting that is very much Fe^{3+} -like (Dunlap and McGraw 2007). In this sense, the Mössbauer data of atacamaites have much more in common with these impact glasses. Indeed, except for the presence of magnetite in sample J338-23, the shape of all Mössbauer spectra is very similar to the one of Irghizite impact glass (see Fig. 1c, in Dunlap and McGraw 2007).

As shown in Fig. 6b and 6c, the isomer shift and quadrupole splitting for D1 and D2 are distributed around their average values, in accordance with the wide range of local distortion of cation environments observed in glasses. As a result, D1 and D2 may contain small contributions due to tetrahedrally coordinated iron (Fe^{2+} or Fe^{3+}), as already identified in silicate glasses (Johnson and Johnson 2005; Stewart et al. 2003). In addition, although the occurrence of electron delocalization has not been reported for previously studied tektites (Rossano et al. 1999), this effect cannot be neglected in our samples - electron delocalization results in average value of isomer shift (0.5 – 0.9 mm/s) that can be assigned to $\text{Fe}^{2.5+}$ (Dyar et al. 2006). Despite this issue concerning the distribution of hyperfine parameters, an estimate for $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio for the studied samples could be determined if D1 and D2 are associated to Fe^{2+} and Fe^{3+} , respectively, based on the average values of hyperfine parameters as previously mentioned. Thus, considering the relative areas for D1 and D2 (Table 3), $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio ranges from 0.282 (for sample PT2d) up to 0.857 (for sample J338-23). $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ can be estimated between 22% (for PT2d) and 36% (for J338-23), taking $\text{Fe}_{\text{total}} = \text{Fe}^{3+} + \text{Fe}^{2+}$. The average $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ ratio is $27.7 \pm 5.4\%$ for the three typical atacamaite samples (i.e. the ones with magnetic susceptibility between 176 and 272 $10^{-9} \text{ m}^3/\text{kg}$, namely JG2h, PT2d, and K51f). These ratios are considerably higher than the ones already reported for tektites from other strewnfields, whose $\text{Fe}^{3+}/\text{Fe}^{2+}$ (or $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$) ratios are close to zero (Dunlap and Sibley 2004; Giuli et al., 2002).

231

232 6. Dating

233 The fission-track dating method, applied successfully to a variety of impact glasses (e.g., Folco
234 et al., 2011), was used on two samples collected 3 km apart. The plateau corrected fission-track
235 ages (Storzer and Wagner, 1969) are 8.08 ± 0.54 Ma and 7.57 ± 0.52 Ma ($\pm 1\sigma$), consistent within
236 1σ error, and with an average 7.83 ± 0.26 Ma (Table 4).

237

238 7. Discussion

239 7.1. Nature of atacamaites

240 Petrological and geochemical characteristics of atacamaites, such as the occurrence of
241 lechatelierite that evidence temperatures above 1700°C (Macris et al., 2014) and the low water
242 content (below 200 ppm) exclude a volcanic origin and indicate formation by hypervelocity
243 impact. Such high temperatures may also be reached naturally by lightning, but the
244 morphology, texture and spatial repartition of atacamaites preclude that they are fulgurites.
245 Compositions in major and trace elements, including the REE patterns, suggest a relatively
246 homogeneous lithology for the target rocks, superimposed with a Fe, Ni, and Co extraterrestrial
247 contamination (Fig. 3-5). Although atacamaites and local Andean dacites have whole rock, Sr
248 and Nd isotopic compositions in the same ranges, no lava with exactly the same compositions
249 has yet been identified in the existing database (Oliveiros et al., 2020).

250 7.2. Impactor

251 The enrichment in Ni and Co in atacamaites (2148 ppm and 182 ppm, respectively, on average,
252 and up to 4800 ppm and 400 ppm in the most magnetic samples) compared to dacites, and the
253 strong correlation between Fe, Ni and Co contents indicate a significant contamination by an

extraterrestrial impactor rich in Fe, Ni and Co (Fig. 3). Although we do not know the composition of the target, it is necessarily a dacitic rock that has practically no Ni and Co compared to the impactor. Therefore, the Ni/Co ratio of the impactor can be estimated from the Ni/Co ratio of the most impactor-rich atacamaïtes. This ratio, computed for atacamaïtes with Ni content above 2500 ppm is $\text{Ni/Co}=12.0\pm0.2$ (1σ , $n=5$). The Ni/Co ratio of the impactor (12.0 ± 0.2) is inconsistent with a chondritic projectile characterized by Ni/Co ratios around 21 (e.g., Wasson and Kallemeyn, 1988). Similarly, the absence of enrichment in Cr precludes a chondritic impactor (Fig. 3C). Therefore, the geochemical data point to an iron impactor. Under the reasonable assumption that Fe, Ni, and Co are the only significant elements in the impactor and mixing lines as exemplified in Figure 3, the bulk composition of the impactor is estimated to 94.15 wt.% Fe, 5.4 wt.% Ni, 0.45 wt.% Co.

The 5.4 wt.% Ni content and the 12.0 Ni/Co ratio of the impactor allow to constrain more precisely the nature of the impactor. The only iron meteorite groups with similar Ni content (<7.5 wt.%) are IC, IIAB, and IIG groups with average Ni contents of 6.50 ± 0.27 wt.% (1σ , $n=41$ analyses), 5.70 ± 0.33 wt.% ($n=274$), 4.53 ± 0.44 wt.% ($n=18$), respectively (Koblitz, 2005; Gattacceca et al., 2018, Wasson et al., 2007). The average Ni/Co ratio for IC, IIAB, and IIG meteorites are 14.17 ± 0.68 ($n=20$), 12.41 ± 0.75 ($n=156$), 8.97 ± 0.79 ($n=8$), respectively (Koblitz, 2005; Gattacceca et al., 2018; Wasson et al., 2007). The best fit is clearly with IIAB meteorites. In particular, no IC meteorite has $\text{Ni/Co}<13.4$, and no IIG meteorite has $\text{Ni/Co}>10.8$. Only two meteorites from of the IAB complex, out of 537 analyses, have Ni content below 6 wt.%, and only 5, out of 326 analyses, have $\text{Ni/Co}<13$ (Koblitz, 2005). Therefore, this group is not considered as a candidate impactor for the atacamaïtes. In conclusion, the IIAB iron group is the most likely candidate for the impactor that formed the atacamaïtes.

Assuming that all the Ni was provided by the meteorite, an average of 5 wt.% impactor contamination can be estimated for atacamaïtes (range 0.8 % to 9 %). This elevated

contamination level is in the same range as glasses from small size craters like the 45 m-diameter Kamil crater (Fazio et al., 2016) or the 120 m-diameter Wabar crater (Mittlefeldt et al., 1992).

7.3. Nomenclature and petrogenesis

A number of criteria are used to differentiate tektites from other splash-form impact glasses (e.g., Koeberl, 1994). Atacamaites have similarities with tektites: a water content of 177 ± 32 ppm that is similar to the content of 140 ± 80 ppm in tektites (Beran and Koeberl, 1997), distribution over a relatively large strewnfield (similar to ivorite and belizite strewnfields, Table 1), absence of relict grains or mineral inclusion in most samples.

Atacamaites also have similarities with more proximal splash-form impact glasses. They show small-scale chemical heterogeneities due to a strong contamination by the impactor, while only minor contamination is reported in tektites.

The redox state of Fe determined by Mössbauer spectroscopy in 5 samples, including two very magnetic ones, yields a ratio of $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ between 22% and 36% (average $27.7 \pm 5.4\%$ for the three typical samples). This $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ ratio of $27.7 \pm 5.4\%$ show that atacamaites are also much more oxidized than tektites whose oxidation ratios are near zero (Table 1). Atacamaites contain Fe oxides inclusions more frequently than tektites where their occurrence is extremely rare. As a consequence, they are more magnetic than tektites, and their magnetic properties are more variable, especially for small specimens (Rochette et al., 2015).

Beside tektites *sensu stricto*, the occurrences of macroscopic splash-form impact glasses, are limited (Table 1). Millimeter-sized ballistic ejecta are found around the Wabar impact craters under the form of glassy droplets (Mittlefeldt et al., 1992), but these are limited to a few hundred meters around three small craters with maximum diameter 120 m (Gnos et al., 2013).

Glass with crude splash-forms is also found over limited areas on the rims of the 390 m-diameter Aouelloul crater (Koeberl et al., 1998). Centimeter-sized splash-form glasses are found over a much wider area ($\sim 400 \text{ km}^2$) around the 1.2 km-diameter Darwin crater (Taylor and Solomon, 1962; Howard, 2009). The impact glasses with closest similarity to atacamaites are irghizites, associated with the 14 km-diameter Zhamanshin crater in Kazakhstan (Bouska et al., 1981). Irghizites and atacamaites share similar morphologies (including presence of small attached spherules, Fig. 2a), and important contamination by the impactor (Schulz et al., 2020). A significant difference is the extent of the strewnfield ($1\text{-}2 \text{ km}^2$ for irghizites vs. 650 km^2 for Atacamaites).

This inventory of tektites and other splash-form impact glasses (Table 1) confirms that it is necessary to combine a number of criteria to discriminate the two categories (following Koeberl, 1994). Chemical homogeneity is a tektite attribute, but it is hard to quantify this homogeneity, and tektites may be heterogeneous (e.g., North American ones, see Albin et al., 2000, and Muong Nong tektites, see Koeberl, 1992). Water content may be ambiguous as non-tektite glasses can be as dry as tektites (Table 1). The reduced character is not exclusive as well, as the Darwin glass is as reduced as tektites (e.g., Rochette et al. 2015). Another criterion may be the distance from the crater that is at least an order of magnitude higher for tektites, but this criterion cannot be strictly applied when the crater location is unknown. A final criterion is crater size, with tektites being associated to craters larger than 10 km. Both criteria cannot be used when the crater is missing, as for atacamaites. In fact, the only other cases of macroscopic non tektite impact glasses without known source crater are Libyan desert glass (e.g., Barrat et al., 1997), and urengoites (e.g., Deutsch et al., 1997), two glasses for which splashforms are not established. The smaller size range (the largest atacamaites are about the size of the smallest tektites) as well as presence of contorted shapes seems to be good criteria for non-tektite material. In addition to the oxidized character and the high impactor

contamination observed in atacamaites, this clearly precludes the classification of atacamaites as tektites.

7.4. Source impact crater

Considering our fission track age for the atacamaites (7.83 ± 0.26 Ma) compared to erosion rates < 1 m/Ma measured in the hyper-arid part of the Atacama Desert (e.g., Dunai et al., 2005), a ~ 10 km diameter (Zhamanshin size) crater and the associated ~ 400 m deep depression should still be visible in the field and on satellite images. On the other hand, published erosion rates were obtained on surfaces specially selected for their stable morphology. Areas with steep slope or low relative altitude may have higher erosion rates or may have accumulated post 8 Ma sediments. Search for impact breccia or non-ejected impact glass were also inconclusive despite several weeks of field work. The failure to detect a candidate source crater for atacamaites suggests it may have been much smaller than 10 km, in the size range of Darwin crater (1.2 km diameter) that produced a ~ 400 km² strewnfield with $\sim 15\%$ of splash-form (Howard, 2009). Modeling shows that cm-sized particles for such small craters can indeed be ejected for several tens of km (Shuvalov and Dypvik, 2013). Finding such delicate glass ejecta present at the surface of Atacama Desert since nearly 8 Ma points toward the extreme stability of Atacama Desert surfaces, already demonstrated by elevated cosmogenic nuclide contents (Dunai et al., 2015), high meteorite densities (Hutzler et al., 2007), and old meteorite terrestrial ages (Drouard et al., 2019).

8. Conclusions

Atacamaites are cm-sized glassy splash-form ejecta found over at least 650 km² in the Central Depression of the Atacama Desert. They are the product of the fusion and ejection of local andesitic rocks by the hypervelocity impact of an iron meteoroid that occurred at ~ 7.8 Ma. The

most likely nature of the impactor is the IIAB iron group. No source crater has been identified so far, despite its likely proximal location. Atacamaïtes do not qualify as tektites *sensu stricto* because of their smaller size, more oxidized character, and high contamination by the impactor. The discovery of atacamaïtes adds a new example of a significantly large strewnfield of ejected tektite-like glass that does not meet a number of criteria to qualify as tektite. Following Rochette et al. (2015), we propose to categorize such objects as “tektoids”, to shorten the description as “non tektite splash-form impact glasses” and to emphasize their similar aspect to tektites. Better understanding of the specificities of atacamaïtes should come from finding the source crater or from our ongoing exploration of the variability of atacamaïtes within their strewnfield (geochemistry, contamination level, size distribution, morphology, ...). The characteristics of atacamaïtes increase the diversity of known impact glasses and hold crucial information to further understand the mechanisms of formation of impact glasses in general, and the consequences of terrestrial impacts on the environment.

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FIGURE CAPTIONS

Fig. 1. Map of atacamaite strewnfield. Its estimated limits are indicated by the solid line. Geological information is from Espinoza et al. (2012).

Fig. 2. Morphologies and petrography of atacamaites. (a) Macroscopic images. (b) Transmitted light image of a thick section evidencing compositional schlieren and bubbles. (c) Backscatter electron image of a sectioned typical atacamaite. (d) Transmitted plane polarized light image of a lechatelierite inclusion. (e) Backscatter electron image of Fe oxides in a highly magnetic atacamaite.

Fig. 3. Atacamaite geochemistry. Ni (a), Co (b), Cr (c) contents vs. Fe content. The linear fits are for ICP-AES data. The fields for pre-Pliocene lavas ($\text{SiO}_2=60\text{--}70$ wt.%, from Oliveiros et al., 2020) are shown for comparison. Note that no Cr enrichment is apparent, consistent with an iron impactor.

Fig. 4. REE concentrations in 12 atacamaites. Concentrations are normalized to CI chondrites (Barrat et al., 2012).

Fig. 5. Sr and Nd isotopic compositions of atacamaites compared with those of pre-Pliocene Andean volcanics (Oliveiros et al., 2020).

Fig. 6. (a) Room temperature ^{57}Fe Mössbauer spectrum for atacamaite sample PT7b. (b) Three-dimensional representation of the total probability distribution $P(\delta, \Delta)$ for PT7B sample as obtained by means of x-VBF method. (c) Contour plots in isomer shift (δ), quadrupole splitting (Δ) plane. For $P(\delta, \Delta) < 0.55$, the contour lines are shown as solid lines. For $P(\delta, \Delta) > 0.55$, the contour lines are shown as broken lines. All lines are spaced at intervals of 0.11.

References

- Albin, E.F., Norman, M.D., Roden, M. 2000. Major and trace element compositions of georgiaites : clues to the source of North American tektites. *Meteorit. Planet. Sci.* 35, 795–806.
- Anders, E., Grevesse, N., 1989. Abundances of the elements: meteoritic and solar. *Geochim. Cosmochim. Acta* 53, 197–214.
- Barrat, J.-A., Jahn, B.M., Amossé, J., Rocchia, R., Keller, F., Poupeau, G.R., Diemer, E., 1997. Geochemistry and origin of Libyan Desert glasses. *Geochim. Cosmochim. Acta* 61, 1953–1959.

406 Barrat, J.-A., Zanda, B., Moynier, F., Bollinger, C., Liorzou, C., Bayon, G., 2012.
 407 Geochemistry of CI chondrites: Major and trace elements, and Cu and Zn isotopes.
 408 *Geochim. Cosmochim. Acta* 83, 79–92.

409 Barrat, J.-A., Dauphas, N., Gillet, P., Bollinger, C., Etoubleau, J., Bischoff, A., Yamaguchi,
 410 A., 2016. Evidence from Tm anomalies for non-CI refractory lithophile element
 411 proportions in terrestrial planets and achondrites. *Geochim. Cosmochim. Acta*, 176, 1–17.

412 Beran, A., Koeberl, C., 1997. Water in tektites and impact glasses by Fourier-transform
 413 infrared spectroscopy. *Meteorit. Planet. Sci.* 32, 211–216.

414 Bigazzi, G., De Michele, V., 1996. New fission-track age determinations on impact glasses.
 415 *Meteorit. Planet. Sci.* 31, 234–236.

416 Bouska, V., Povondra, P., Florenskij, P.V., Randa, Z., 1981. Irghizites and Zhamanshinites:
 417 Zhamanshin crater, USSR. *Meteoritics* 16, 171–1884.

418 Braukmüller, N., Wombacher, F., Heze, D.C., Escoube, R., Münker, C., 2018. The chemical
 419 composition of carbonaceous chondrites: Implications for volatile element depletion,
 420 complementarity and alteration. *Geochim. Cosmochim. Acta*. 239, 17–48.

421 Chao, E.C.T., Dwornik, E.J., Merrill, C.W., 1966. Nickel-iron spherules from Aouelloul glass.
 422 *Science* 154, 759–760+765.

423 Cornell, R.M., Schwertmann, U., 2003. The iron oxides: structure, properties, reactions,
 424 occurrences and uses. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KgaA.

425 Cotten, J., Le Dez, A., Bau, M., Caroff, M., Maury, R., Dulski, P., Fourcade, S., Bohn, M.,
 426 Brousse, R., 1995. Origin of rare-earth element and yttrium enrichments in subaerial
 427 exposed basalts: evidence from French Polynesia. *Chemical Geol.* 119, 115–138.

428 Deutsch, A., Ostermann, M., Masaitis, V.L., 1997. Geochemistry and neodymium-strontium
 429 isotope signature of tektite-like objects from Siberia (urengoites, South-Ural glass).
 430 *Meteorit. Planet. Sci.* 32, 679–686.

431 Dressler, B.O., Reimold, W.U., 2001. Terrestrial impact melt rocks and glasses. *Earth Sci. Rev.*
 432 56, 205-284.

433 Drouard, A., Gattacceca, J., Hutzler, A., Rochette, P., Braucher, R., Bourlès, D., ASTER Team,
 434 Gounelle, M., Morbidelli, A., Debaille, V., Van Ginneken, M., Valenzuela, M., Quesnel,

435 Y., Martinez, R., 2019. The meteorite flux of the past 2 m.y. recorded in the Atacama
 436 Desert. *Geology* 47, 673–676.

437 Dunlap, R.A., Sibley, A.D.E., 2004. A Mössbauer effect study of Fe-site occupancy in
 438 Australasian tektites. *J. Non-Crystalline Solids* 337, 36–41.

439 Dunlap, R.A., McGraw, J.D., 2007. A Mössbauer effect study of Fe environments in impact
 440 glasses. *J. Non-Crystalline Solids* 353, 2201–2205.

441 Dyar, M.D., Agresti, D.G., Schaefer, M.W., Grant, C.A., Sklute, E.C., 2006. Mössbauer
 442 spectroscopy of earth and planetary materials. *Annual Rev. Earth and Planet. Sci.* 34, 83-
 443 125.

444 Espinoza, F.G., Matthews, S.J., Cornejo P.P., 2012. Carta Los Vientos, Región de Antofagasta.
 445 Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica
 446 138: 72 p., scale 1:100.000. Santiago.

447 Fazio, A., D'Orazio, M., Cordier, C., Folco, L., 2016. Target-projectile interaction during
 448 impact melting at Kamil Crater, Egypt. *Geochim. Cosmochim. Acta* 180, 33–50.

449 Folco, L., Bigazzi, G., D'Orazio, M., Balestrieri, M.L., 2011. Fission track age of
 450 Transantarctic Mountain microtektites. *Geochim. Cosmochim. Acta* 75, 2356–2360.

451 Gattacceca, J., Bouvier, A., Grossman, J., Metzler, K., Uehara, M. 2018. The Meteoritical
 452 Bulletin, No 106. *Meteorit. Planet. Sci.* 54, 469–471.

453 Gentner, W., Storzer, D. Wagner, G.A., 1969. New fission track ages of tektites and related
 454 glasses. *Geochim. Cosmochim. Acta* 33, 1075–1081.

455 Giuli, G., Pratesi, G., Cipriani, C., Paris, E., 2002. Iron local structure in tektites and impact
 456 glasses by extended X-ray absorption fine structure and high-resolution X-ray absorption
 457 near-edge structure spectroscopy. *Geochim. Cosmochim. Acta* 66, 4347–4353.

458 Gnos, E., Hofmann, B.A., Halawani, M.A., Tarabulsi, Y., Hakeem, M., Al Shanti, M., Greber,
 459 N.D., Holm, S., Alwmark, C., Greenwood, R.C., Ramseier, K., 2013. The Wabar impact
 460 craters, Saudi Arabia, revisited. *Meteorit. Planet. Sci.* 48, 2000–2014.

461 Haines, P.W., Jenkins, R.J., Kelley, S.P., 2001. Pleistocene glass in the Australian desert: the
 462 case for an impact origin. *Geology* 29, 899–902.

463 Howard, K.T., 2009. Physical distribution trends in Darwin glass. *Meteorit. Planet. Sci.* 44,
 464 115–129.

465 Hutzler, A., Gattacceca, J., Rochette, P., Braucher, R., Carro, B., Christensen, E., Cournède,
 466 C., Gounelle, M., Laridhi-Ouazaa, N., Martinez, R., Warner, M., Bourlès, D., 2016.
 467 Description of a very dense meteorite collection area in western Atacama: insight into the
 468 long-term composition of the meteorite flux to Earth. *Meteorit. Planet. Sci.* 51, 468–482.

469 Johnson, J.A., Johnson, C.E., 2005. Mössbauer spectroscopy as a probe of silicate glasses. *J.*
 470 *Physics: Condensed Matter* 17, R381–R412.

471 Koeberl, C. 1992. Geochemistry and origin of Muong Nong-type tektites. *Geochim.*
 472 *Cosmochim. Acta* 56:1033–1064.

473 Koeberl, C., 1994. Tektite origin by hypervelocity asteroidal or cometary impact. Target rocks,
 474 source craters, and mechanisms, *in* Dressler, B.O., Grieve, R.A.F., and Sharpton, V.L.,
 475 eds., *Large Meteorite Impacts and Planetary Evolution*: Geological Society of America
 476 Special Paper 293, p. 133-152.

477 Koeberl, C., 2014. The Geochemistry and Cosmochemistry of Impacts, in *Planets, Asteroids,*
 478 *Comets and The Solar System*, *in* Andrew M. Davis, ed., *Treatise on Geochemistry*
 479 (Second Edition), v. 2, p.73-118.

480 Koeberl, C., Bottomley, R., Glass, B.P., Storzer, D., 1997. Geochemistry and age of Ivory
 481 Coast tektites and microtektites. *Geochim. Cosmochim. Acta* 61, 1745–1772.

482 Koeberl, C., Reimold, W.U., Shirey, S.B., 1998. The Aouelloul crater, Mauritania: on the
 483 problem of confirming the impact origin of a small crater. *Meteorit. Planet. Sci.* 33, 513–
 484 517.

485 Koeberl, C., Crosta, A.P., Schulz, T., 2019. Geochemical investigation of the atacamaites, a
 486 new impact glass occurrence in South America. 50th Lunar Planet. Sci. Conf., abstract
 487 1255.

488 Koblitz, J. 2005. MetBase – Meteorite Data Retrieval Software, version 7.1. Bremen, Germany
 489 (CD-ROM).

490 Lagarec, K., Rancourt, D.G. 1997. Extended Voigt-based analytic lineshape method for
 491 determining N-dimensional correlated hyperfine parameter distributions in Mössbauer
 492 spectroscopy. *Nuclear Instruments Methods Phys. Res. Section B* 126, 266–280.

493 Laurenzi, A., Balestrieri, M.L., Bigazzi, G., Hadler Neto, J.C., Iunes, P.J., Norelli, P., Oddone,
 494 M., Osorio Araya, A.M., Viramonte, J.G., 2007. New constraints on ages of glasses
 495 proposed as reference materials for fission-track dating. *Geostandards Geoanalytical Res.*
 496 31, 105–124.

497 Macris, C.A., Asimow, P.D., Badro, J., Eiler, J.M., Zhang, Y., Stolper, E.M., 2018. Seconds
 498 after impact: Insights into the thermal history of impact ejecta from diffusion between
 499 lechatelierite and host glass in tektites and experiments. *Geochim. Cosmochim. Acta* 241,
 500 69–94.

501 Magna, T., Zak, K., Pack, A., Moynier, F., Mougél, B., Peters, S., Skala, R., Jonasova, S.,
 502 Mizera, J., Randa, Z., 2017. Zhamanshin astrobleme provides evidence for carbonaceous
 503 chondrite and post-impact exchange between ejecta and Earth's atmosphere. *Nature*
 504 *Communications* 88, article no. 227.

505 Murali, A.V., Zolensky, M.E., Blanchard, D.P., 1987. Tektite-Like Bodies at Lonar Crater,
 506 India, Implications for the Origin of Tektites. *J. Geophys. Res.* 92, no. B4, E729–E735.

507 Mittlefehldt, D.W., See, T.H., Hörz, F., 1992. Dissemination and fractionation of projectile
 508 materials in the impact melts from Wabar Crater, Saudi Arabia. *Meteoritics* 27, 361–370.

509 Oliveros, V., Moreno-Yaeger, P., Flores, L., 2020. *Igneous Rock Associations* 25. Pre-Pliocene
 510 Andean Magmatism in Chile. *Geoscience Canada*, 47, 65–82.

511 Osinski, G.R., Kieniewicz, J., Smith, J.R., Boslough, M., Eccleston, M., Scharcz, H.P.,
 512 Kleindienst, M.R., Haldemann, A.F.C., Churcher, C.S., 2008. The Dakhleh Glass: Product
 513 of an impact airburst or cratering event in the Western Desert of Egypt? *Meteorit. Planet.*
 514 *Sci.* 43, 2089–2107.

515 Rochette, P., Gattacceca, J., Devouard, B., Moustard, F., Bezaeva, N., Cournède, C., Scaillet,
516 B., 2015. Magnetic properties of tektites and other related impact glasses. *Earth Planet.*
517 *Sci. Lett.* 432, 381–390.

518 Rochette, P., Bezaeva, N., Kosterov, A., Gattacceca, J., Masaitis, V., Badyukov, D.D., Giuli,
519 G., Lepore, G.O., Beck, P., 2019. Magnetic Properties and Redox State of Impact Glasses:
520 A Review and New Case Studies from Siberia. *Geosciences* 9, article no. 225.

521 Rochette, P., Beck, P., Braucher, R., Cornec, J., Debaille, V., Devouard, B., Gattacceca, J.,
522 Jourdan, F., Moustard, F., Moynier, F., Nomade, S., Reynard, B., 2021. A new tektite
523 strewn-field and source crater couple discovered in Central America: insights into the
524 tektite generation process and its ubiquity. *Commun. Earth Environ.* 2, 94.
525 Doi:10.1038/s43247-021-00155-1.

526 Roperch, P., Gattacceca, J., Valenzuela, M., Devouard, B., Lorand, J.-P., Arriagada, C.,
527 Rochette, P., Latorre, C., Beck, P., 2017. Surface vitrification caused by natural fires in
528 Late Pleistocene wetlands of the Atacama desert. *Earth and Planetary Science Letters* 469,
529 15–26.

530 Rossano, S., Balan, E., Morin, G., Bauer, J.P., Calas, G., Brouder, C., 1999. ^{57}Fe Mössbauer
531 spectroscopy of tektites. *Phys. Chem. Minerals* 26, 530–538.

532 Sandhu, A.S., Westgate, J.A., Alloway, B.V., 1993. Optimizing the isothermal plateau fission-
533 track dating method for volcanic glass shards. *Nuclear Tracks Radiation Measurements*
534 21, 479–488.

535 Schulz, T., Sackl, F., Fragner, E., Luguët, A., van Acken, D., Begosew, A., Badyukov, D.D.,
536 Koeberl, C., 2020. The Zhamanshin impact structure, Kazakhstan: A comparative
537 geochemical study of target rocks and impact glasses. *Geochim. Cosmochim. Acta* 268,
538 209–229.

539 Schultz, P.H., Zárate, M., Hames, B., Koeberl, C., Bunch, T., Storzer, D., Renne, P., Wittke,
540 J., 2004. The Quaternary impact record from the Pampas, Argentina. *Earth Planet. Sci.*
541 *Lett.* 219, 221–238.

542 Shuvalov, V., Dypvik, H., 2013, Distribution of ejecta from small impact craters. *Meteorit.*
543 *Planet. Sci.* 48, 1034–1042.

544 Stewart, S.J., Cernicchiaro, G., Scorzelli, R.B., Poupeau, G., Acquafredda, P., De Francesco,
545 A., 2003. Magnetic properties and ^{57}Fe Mössbauer spectroscopy of Mediterranean
546 prehistoric obsidians for provenance studies. *J.Non-Crystalline Solids* 323, 188–192.

547 Storzer, D., Wagner, G.A., 1970. Fission track ages and ages of deposition of deep-sea
548 microtektites. *Science* 168, 359–361.

549 Storzer, D., Poupeau, G., 1973. Ages-plateau de minéraux et verres par la méthode des traces
550 de fission. *C. R. de l'Académie des Sciences Paris* 276 (D), 317–319.

551 Storzer, D., Wagner, G.A., 1969. Correction of thermally lowered fission-track ages of tektites.
552 *Earth Planet. Sci. Letters* 5, 463–468.

553 Taylor, S.R., Solomon, M., 1962. Geochemical and geological evidence for the origin of
554 Darwin glass. *Nature* 196, 124–126.

555 Wasson, J.T., Kallemeyn, G.W., 1988. Compositions of chondrites. *Philosoph. Transactions*
556 *Royal Society London* A325, 535–544.

557 Wasson, J.T., Huber, H., Malvin, D.J., 2007. Formation of IIAB iron meteorites. *Geochim.*
558 *Cosmochim. Acta* 71, 760–781.

560 **Table 1.** Characteristics of known splash-form impact glasses.

	Fe ³⁺ /Fe _{total}	water (ppm)	magnetic susceptibility (10 ⁻⁹ m ³ /kg) mean±SD range		maximum distance from crater (km)	crater diameter (km)	age (Ma)	impactor
Australasian*	<0.1	156±76	82±10	73-129	≥5000	?	0.788	ordinary chondrite?
belizites*	<0.1	99±31	127±5	112-193	530	14	0.8	ordinary chondrite
ivoirites*	<0.1	23±5	103±12	62-138	320	10.5	1.1	L ordinary chondrite
moldavites*	<0.1	83±17	31±19	25-60	600	24	14.9	achondrite?
North-American*	<0.1	183±77	65±24	43-129	2300	85	35.5	chondrite?
Wabar glass	0.2	?	468±58	125-1025	1.3	0.12	0.005	IIIAB
Darwin glass	<0.1	470	53±23	34-79	35	1.2	0.73	?
irghizites	0.2-0.4	283±173	164±59	45-3320	0	13.5	0.9	carbonaceous chondrite
Aouelloul glass	0.3	350±20	82±9	38-463	0	0.36	3.1	Iron (IIB, IIID?)
atacamaites	0.28±0.05	177±32	191±71	84-20500	≥50	?	7.6	Iron (IIAB)

561 Tektites, indicated by *, and other glasses are listed by increasing age. Other glasses are by
562 alphabetical order. Non-ejected glasses tentatively attributed to impact or airbursts such as
563 Dahkleh (Osinski et al., 2008), Argentinian (Schultz et al., 2004), and Edeowie glasses (Haines
564 et al., 2001) are not listed, also because an alternative formation mechanism by fire and
565 associated surface melting has been proposed for such glasses (Roperch et al., 2017). Magnetic
566 properties from Rochette et al. (2015). Crater diameters, age, maximum distance and impactor
567 type are mostly from Dressler and Reimold (2001) and Koeberl (2014). Fe³⁺/Fe_{total} are from
568 Rochette et al. (2019). Water content are mostly from Beran and Koeberl (1997). Other
569 references used: Howard (2009) for Darwin glass, Gnos et al. (2013) for Wabar glass, Magna
570 et al. (2017) for irghizites, Rochette et al. (2021) for belizites.

571 **Table 2.** Major and trace element abundances of atacamaites (oxides in wt.%, others in ppm).

#	K48k	K51j	K51f	JG2h	PT7e	PT3i	JG2a	PT7b	K51b	PT3b	PT2d	PT2g
χ	188	133	272	176	91	1038	136	3593	167	168	132	147
SiO ₂ *	64.3	66.4	60.1	64.5	68.1	58.2	65.8	60.2	64.1	64.7	66.2	66.3
TiO ₂	0.52	0.53	0.54	0.52	0.54	0.64	0.52	0.50	0.52	0.52	0.52	0.52
Al ₂ O ₃	12.72	12.99	13.28	12.51	13.36	15.91	12.89	12.13	12.83	12.54	12.84	12.67
FeO	9.09	6.88	11.89	9.27	4.58	9.64	7.06	14.18	9.38	8.87	7.28	7.40
MnO	0.08	0.08	0.08	0.07	0.08	0.10	0.08	0.07	0.08	0.08	0.07	0.07
MgO	1.91	1.84	1.45	1.98	2.44	2.06	1.98	1.53	1.95	1.91	1.99	1.96
CaO	4.45	4.32	5.57	4.34	4.45	5.37	4.64	4.87	4.34	4.43	4.36	4.35
Na ₂ O	3.58	3.60	3.54	3.52	3.37	4.12	3.71	3.19	3.47	3.56	3.53	3.57
K ₂ O	2.91	3.06	2.94	2.91	2.97	3.55	3.05	2.67	2.88	2.98	2.89	2.89
P ₂ O ₅	0.10	0.09	0.07	0.08	0.06	0.09	0.06	0.08	0.07	0.10	0.07	0.06
Co	224	133	311	222	45	208	144	409	217	212	150	159
Ni	2735	1545	3838	2636	412	2242	1703	4803	2584	2550	1697	1780
Li	49.34	53.38	56.46	49.86	52.77	64.29	48.11	46.57	46.65	50.66	48.14	48.85
Be	1.96	2.10	2.12	1.96	2.14	2.55	1.92	1.78	1.86	1.99	1.95	1.99
Sc	9.73	9.85	9.76	9.66	10.02	11.46	9.26	8.82	9.50	9.88	9.62	9.58
V	85.58	83.73	86.29	83.25	75.67	91.17	81.14	74.77	80.81	89.26	79.34	81.44
Cr	34.38	27.06	30.11	35.02	18.77	29.25	27.99	29.47	32.28	34.03	27.45	28.64
Cu	14.29	12.19	16.77	11.88	3.78	13.15	12.06	15.24	12.27	17.11	10.29	12.10
Zn	10.41	7.07	10.81	6.15	3.93	9.51	5.96	8.78	7.03	12.87	6.63	7.36
Ga	14.36	12.36	16.10	12.34	7.46	13.73	13.14	14.33	12.85	16.07	11.78	12.37
Rb	97.66	98.71	99.40	90.15	83.82	112.62	94.86	84.68	91.76	102.95	92.60	95.04
Sr	226	231	255	214	228	283	220	227	221	230	214	223
Y	38.74	39.78	38.54	38.37	41.52	47.67	37.45	33.99	37.63	39.59	38.34	38.66
Zr	178	178	195	172	175	231	167	167	168	180	169	172
Nb	11.41	11.13	11.83	11.03	11.55	13.56	10.66	10.30	10.62	11.38	10.77	10.91
Cs	5.48	5.28	4.98	4.89	4.25	5.71	6.26	5.29	5.96	6.81	5.95	6.02
Ba	635	650	631	616	723	769	623	589	624	652	552	633
La	37.12	38.35	36.30	36.67	41.85	45.59	36.61	33.35	36.70	38.45	36.90	37.60
Ce	69.61	74.78	72.30	69.17	77.76	88.96	69.59	65.65	69.13	73.32	70.12	70.82
Pr	8.18	8.86	8.40	8.30	9.18	10.35	8.34	7.60	8.26	8.73	8.32	8.47
Nd	31.79	34.39	32.79	32.33	35.22	40.82	32.42	29.40	32.22	33.92	32.44	32.81
Sm	6.67	6.94	6.77	6.68	7.45	8.38	6.61	6.03	6.63	7.01	6.67	6.74
Eu	1.09	1.07	1.07	1.08	1.13	1.31	1.05	0.95	1.07	1.12	1.06	1.08
Gd	6.53	6.14	6.12	6.30	6.71	7.60	6.12	5.52	6.19	6.54	6.27	6.25
Tb	1.02	0.96	0.95	0.98	1.05	1.19	0.96	0.87	0.97	1.02	0.98	0.99
Dy	6.09	5.84	5.70	5.98	6.54	7.16	5.79	5.29	5.92	6.26	5.99	6.00
Ho	1.24	1.22	1.18	1.24	1.37	1.50	1.20	1.10	1.23	1.30	1.25	1.26
Er	3.52	3.53	3.42	3.58	4.01	4.31	3.51	3.21	3.55	3.70	3.59	3.59

Yb	3.37	3.60	3.42	3.48	3.86	4.33	3.47	3.19	3.44	3.61	3.50	3.52
Lu	0.49	0.54	0.50	0.51	0.56	0.63	0.51	0.47	0.50	0.53	0.51	0.51
Hf	4.89	5.38	5.71	4.98	5.20	6.62	5.09	4.99	4.97	5.32	5.04	5.04
Ta	0.88	0.95	0.99	0.89	0.94	1.15	0.90	0.86	0.87	0.94	0.89	0.89
Pb	3.12	2.25	2.92	1.65	1.25	2.52	2.09	1.66	2.42	2.65	1.70	1.90
Th	11.42	10.98	11.41	11.25	12.28	13.73	11.21	10.70	11.36	12.21	11.43	11.35
U	1.91	1.80	1.51	1.92	1.73	1.92	1.92	1.39	1.87	2.18	1.85	1.83

χ : magnetic susceptibility in $10^{-9} \text{ m}^3/\text{kg}$. *SiO₂ was not measured and obtained by difference assuming a total of 100 wt.%.

575

576 **Table 3.** Room temperature ^{57}Fe hyperfine parameters for atacamaite samples

Samples	D1			D2			Magnetite								Area ratio
	<δ> (mm/s)	<Δ> (mm/s)	A (%)	<δ> (mm/s)	<Δ> (mm/s)	A (%)	Fe-A				Fe-B				
							<δ> (mm/s)	<Δ> (mm/s)	<B _{hf} > (T)	A (%)	<δ> (mm/s)	<Δ> (mm/s)	<B _{hf} > (T)	A (%)	
															D2/D1
PT7b	1.02	2.07	64	0.52	0.83	36	-	-	-	-	-	-	-	-	0.56
JG2h	1.00	2.00	74	0.56	0.80	26	-	-	-	-	-	-	-	-	0.35
PT2d	0.99	1.95	78	0.53	0.79	22	-	-	-	-	-	-	-	-	0.28
K51f	0.93	2.10	65	0.53	0.76	35	-	-	-	-	-	-	-	-	0.54
J338-23	0.88	2.19	42	0.49	0.78	36	0.32	-0.01	48.6	14	0.70	-0.08	44.7	8	0.86

578

579 < δ >: mean isomer shift relative to alpha-iron, < Δ >: mean quadrupole splitting, < B_{hf} >: mean
580 hyperfine field, A: relative area. The Gaussian widths for the center shift (σ_δ) and quadrupole
581 splitting (σ_Δ) distributions range from 0.15 to 0.30 and 0.15 to 0.43, respectively. The
582 correlation parameter for the x-VBF method are taken to be 0.01 and 0.07 for the D1 and D2
583 distributions, respectively. Typical uncertainties for < δ >, < Δ >, and < B_{hf} > are ± 2 for the last
584 digit. For relative area, uncertainty is $\pm 1\%$.

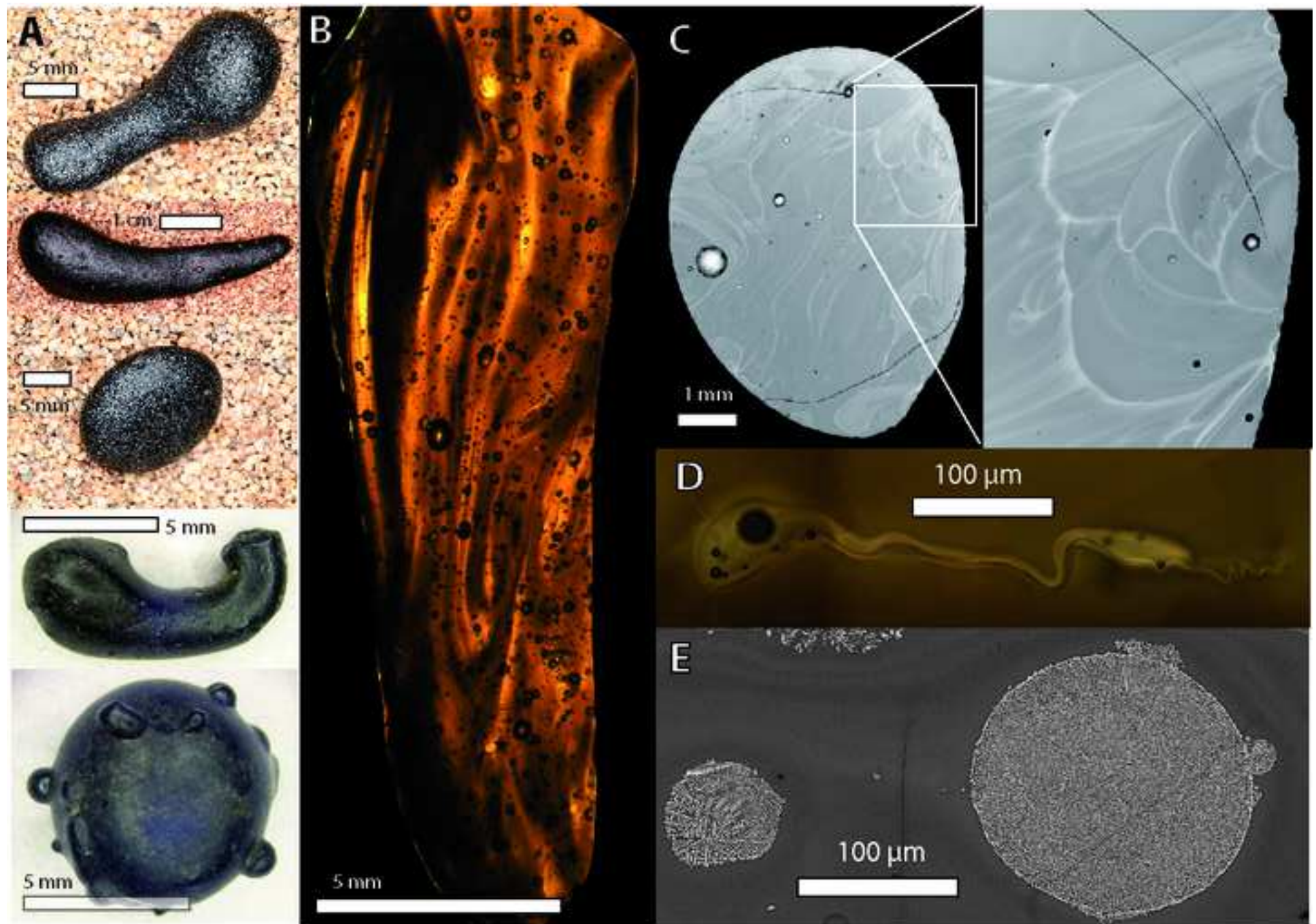
585

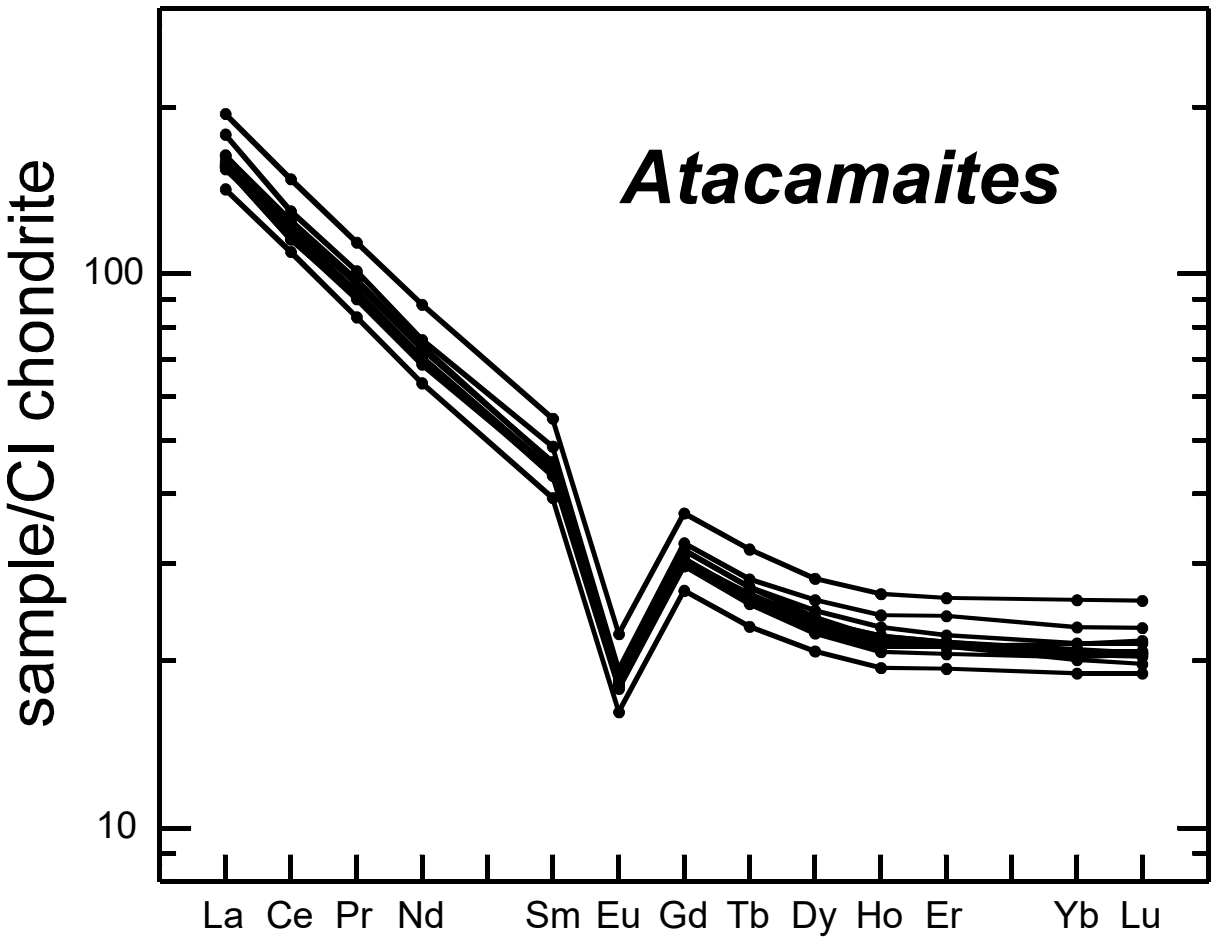
586 **Table 4.** Fission-track dating

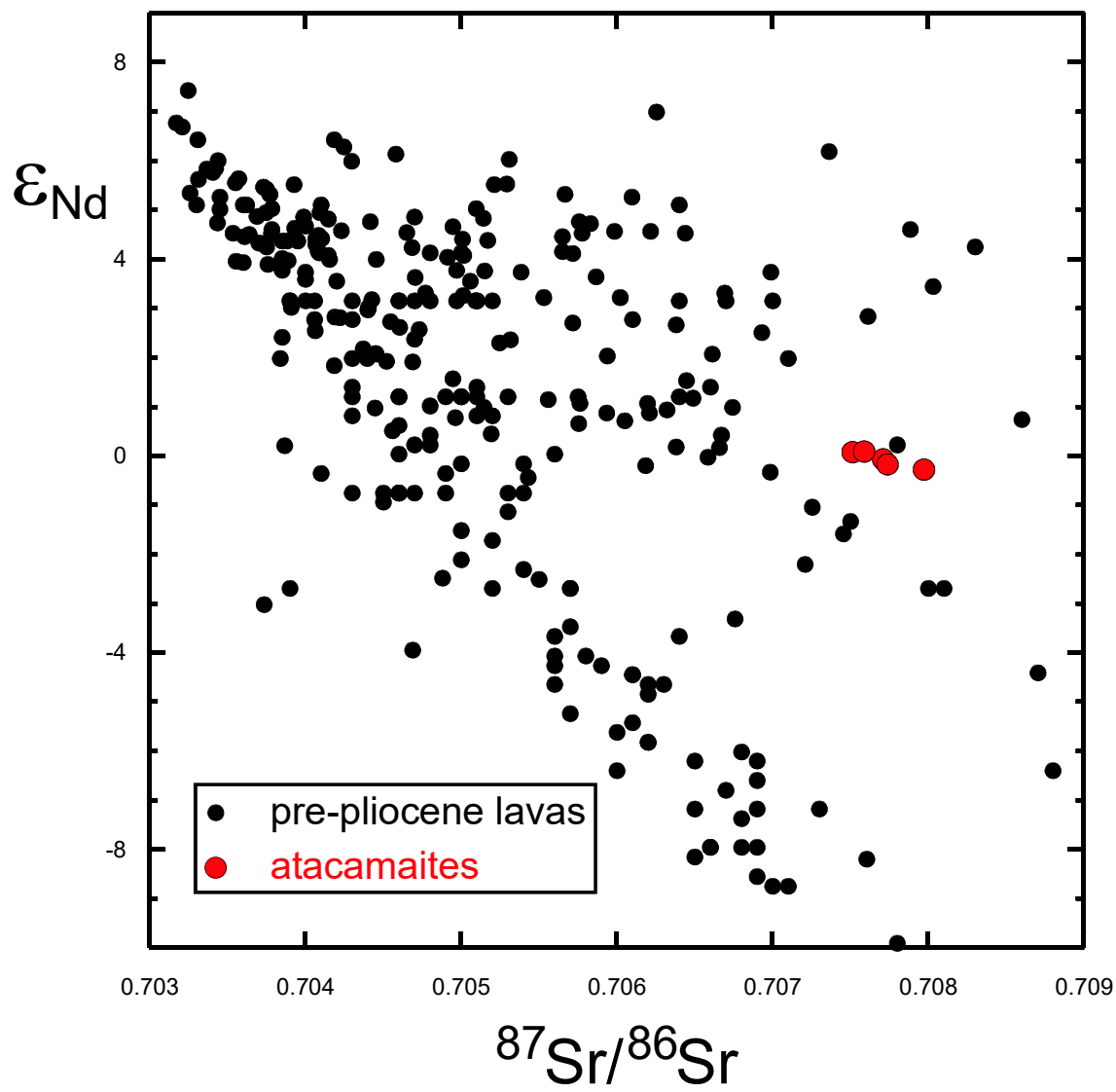
Sample	Heating	ρ_s (cm ⁻²)	n_s	ρ_i (cm ⁻²)	n_i	$p(\chi^2)$ (%)	D_s/D_i	Age ($\pm 1\sigma$) (Ma)
JG26	Ambient	1990	66	183000	1071	66	0.72	3.42 ± 0.43
	4h 220°C	1400	282	54700	1084	7	1.01	8.08 ± 0.54
PT7E	Ambient	2370	329	177000	1041	99	0.83	4.20 ± 0.27
	4h 220°C	1680	260	70100	1108	60	0.97	7.57 ± 0.52

587 Heating: Thermal treatment imposed for plateau age determination; ρ_s (ρ_i): spontaneous
588 (induced) track density; n_s (n_i): spontaneous (induced) tracks counted; $p(\chi^2)$: probability of
589 obtaining χ^2 value testing induced track counts against a Poisson distribution; D_s/D_i :
590 spontaneous to induced track-size ratio. Parameters used for age calculation: $\lambda = 1.55125 \times 10^{-10}$
591 a^{-1} ; $\lambda_F = 8.46 \times 10^{-17} \text{a}^{-1}$; $\sigma = 5.802 \times 10^{-22} \text{cm}^2$; $^{238}\text{U}/^{235}\text{U} = 137.88$. Samples were irradiated
592 in the Lazy Susan (Cd ratio 6.5 for Au and 48 for Co) facility of the Triga Mark II reactor of
593 L.E.N.A., University of Pavia, Italy. The neutron fluence, $\Phi = 5.26 \times 10^{15} \text{cm}^{-2}$, was
594 determined using the NRM IRMM-540 standard glass. Age errors are propagation of Poisson
595 counting errors.

Fig 2







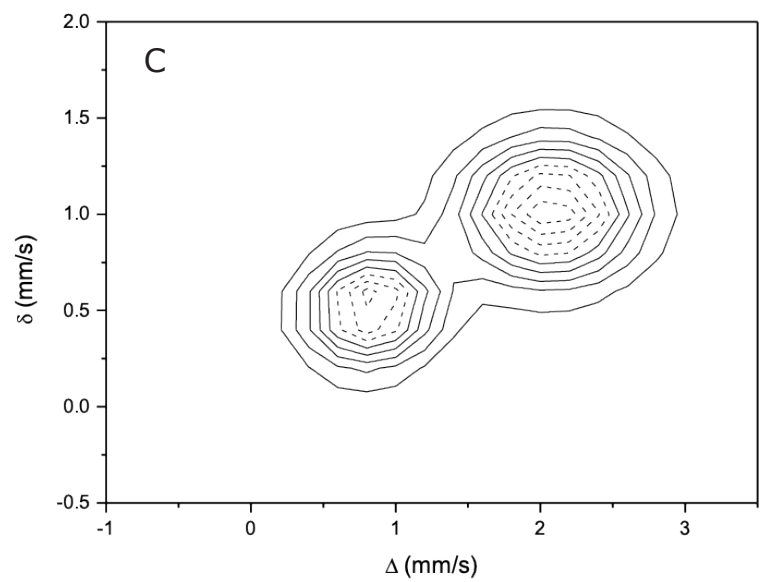
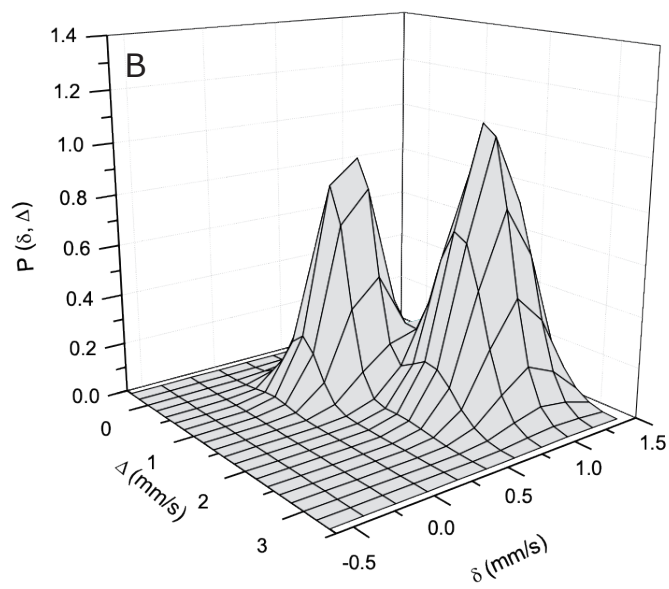
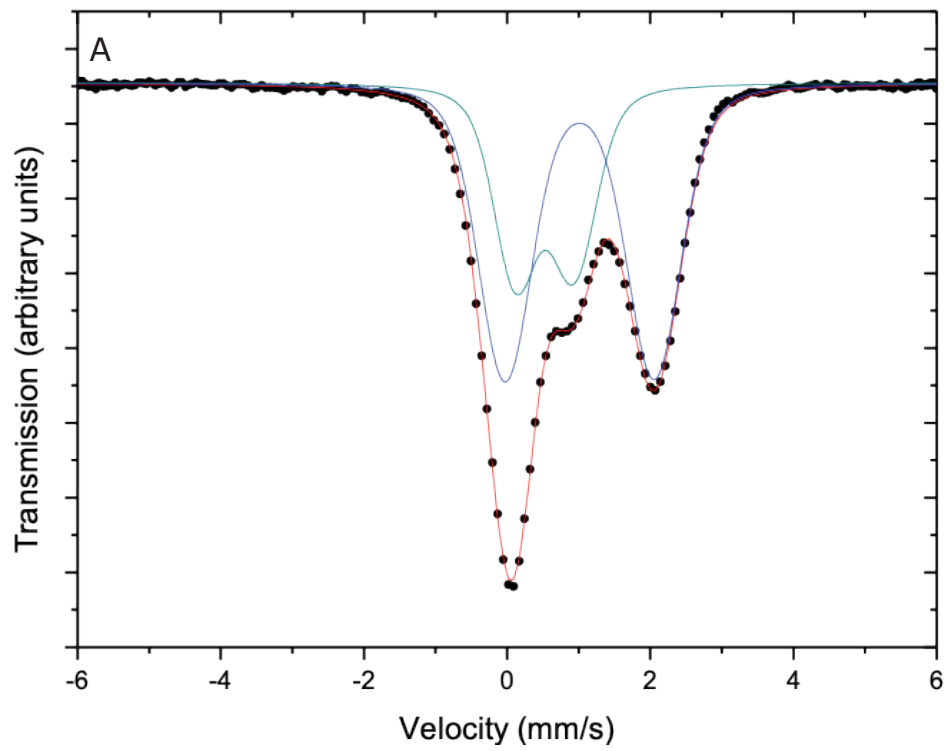
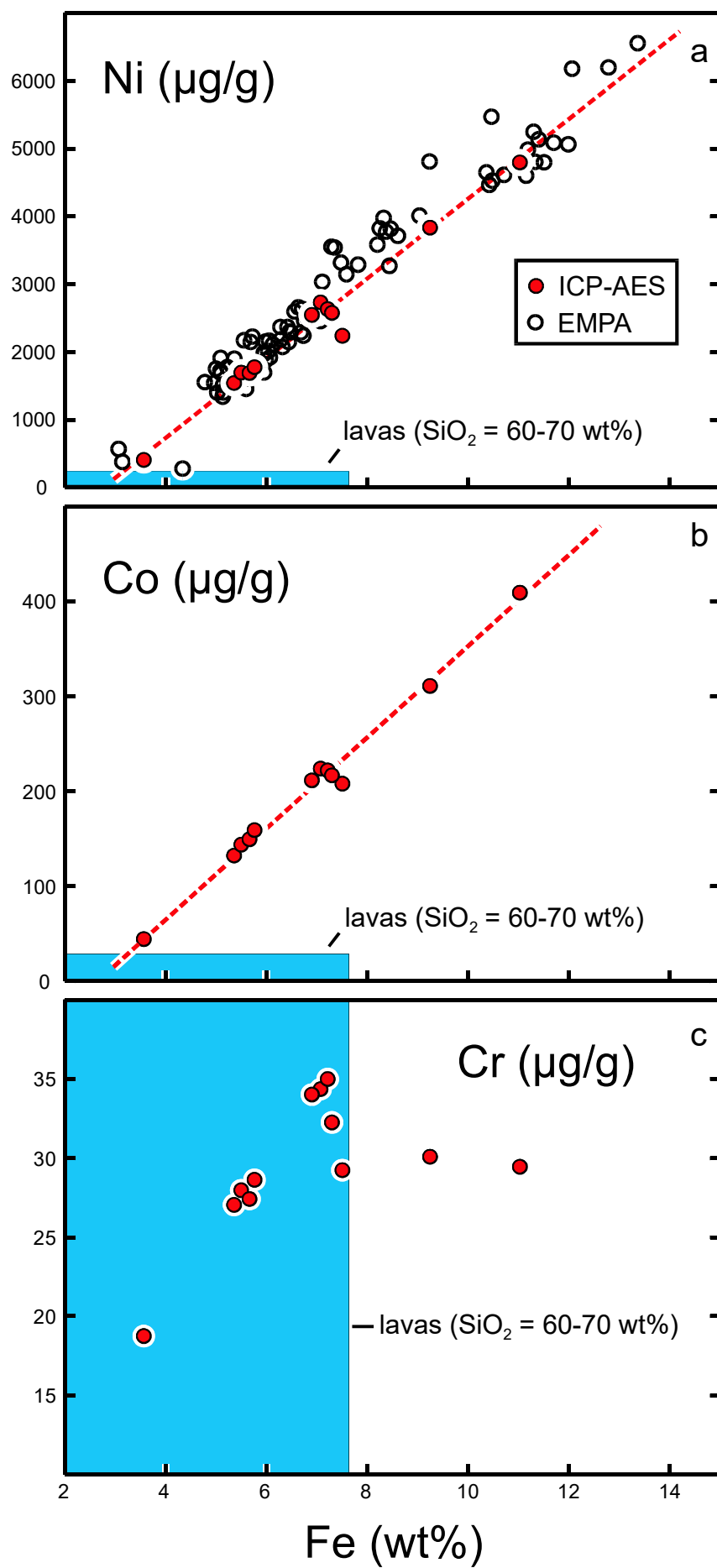
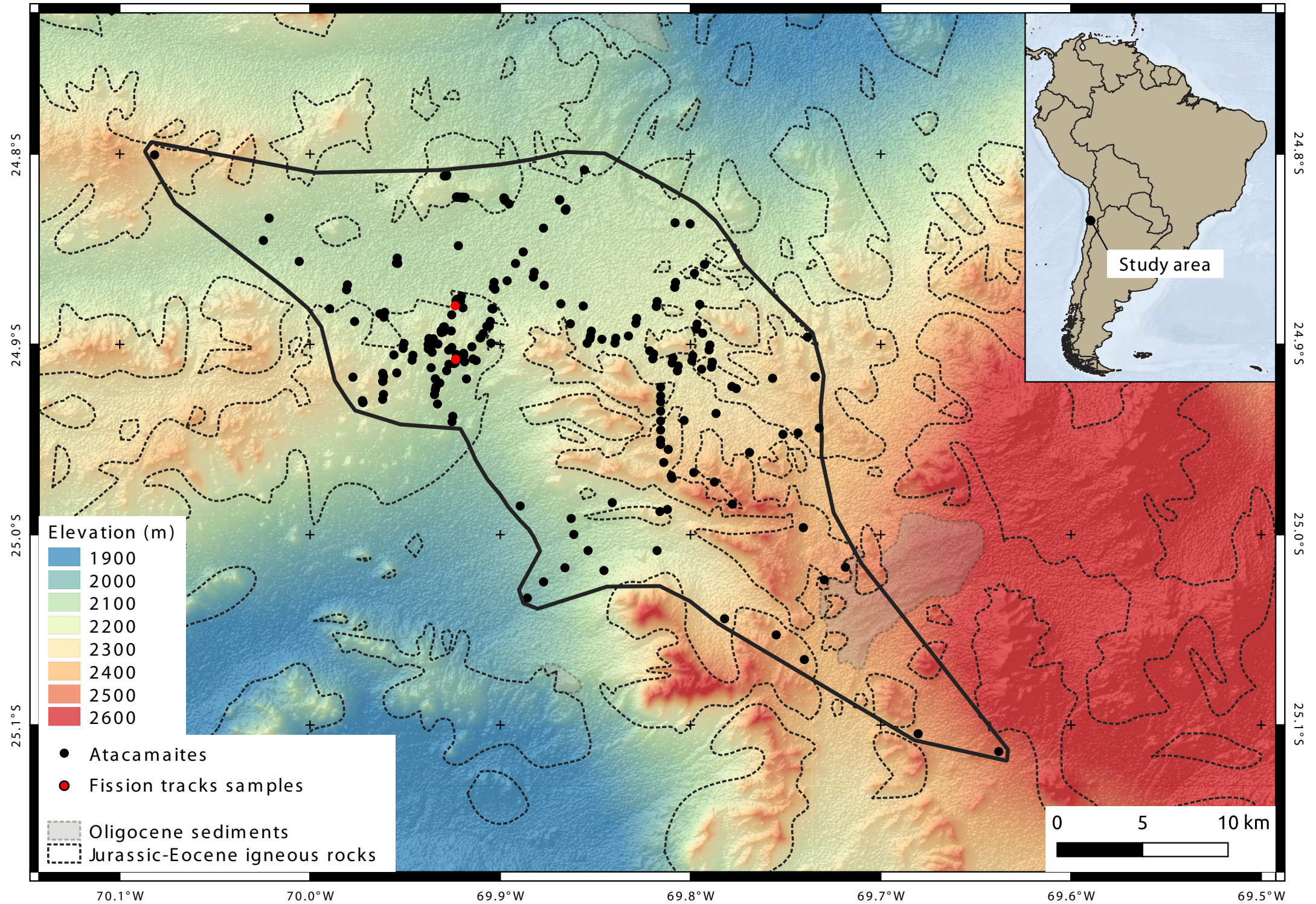


Fig 3







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Figure (high-resolution)
Figure 01 revised.pdf





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