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► To cite this version:

J. Gattacceca, Bertrand Devouard, Jean-Alix J-A Barrat, Pierre Rochette, M.L. Balestrieri, et al.. A 650 km² Miocene strewnfield of splash-form impact glasses in the Atacama Desert, Chile. *Earth and Planetary Science Letters*, 2021, 569, pp.117049. 10.1016/j.epsl.2021.117049 . hal-03265855

HAL Id: hal-03265855

<https://hal.science/hal-03265855v1>

Submitted on 22 Oct 2021

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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

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

3 **J. Gattacceca¹, B. Devouard¹, J.-A. Barrat², P. Rochette¹, M.L. Balestrieri³, G. Bigazzi^{3†},**
4 **G. Ménard¹, F. Moustard¹, E. Dos Santos⁴, R. Scorzelli⁵, M. Valenzuela^{6,7}, M. Gounelle⁸,**
5 **V. Debaille⁹, P. Beck¹⁰, L. Bonal¹⁰, B. Reynard¹¹, M. Warner¹²**

6 *¹CNRS, Aix Marseille Univ, IRD, INRAE, CEREGE, 13545 Aix-en-Provence, France*

7 *²Univ Brest, CNRS, IRD, Ifremer, LEMAR, F-29280 Plouzané, France*

8 *³CNR, Institute of Geosciences and Earth Resources, 56124 Pisa, Italy*

9 *⁴Instituto de Ciência e Tecnologia, Universidade Federal dos Vales do Jequitinhonha e Mucuri*
10 *UFVJM, Diamantina, MG 39100-000, Brazil*

11 *⁵Centro Brasileiro de Pesquisas Físicas – CBPF, Rio de Janeiro, RJ 22290-180, Brazil*

12 *⁶Departamento de Ciencias Geológicas, Universidad Católica del Norte, Av. Angamos 0610,*
13 *Antofagasta, Chile*

14 *⁷Millennium Institute of Astrophysics, Av. Vicuña Mackenna, 4860, Macul, Santiago, Chile*

15 *⁸Muséum national d'Histoire naturelle, Sorbonne Universités, CNRS, IMPMC, 75005 Paris,*
16 *France*

17 *⁹Laboratoire G-Time, Université Libre de Bruxelles, 1050 Brussels, Belgium*

18 *¹⁰Univ. Grenoble Alpes, CNRS, IPAG, 38400 Grenoble, France*

19 *¹¹Univ Lyon, ENSL, UCBL, CNRS, LGL-TPE, 69342 Lyon, France*

20 *¹²NSF National Optical-Infrared Astronomy Research Laboratory, Avda Juan Cisternas 1500,*
21 *La Serena, Chile.*

22 **ABSTRACT**

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

37

38 **1. Introduction**

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

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

49

50 **2. Geological setting, strewnfield, macroscopic description**

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

57 Centimeter-sized dark glassy stones were first noticed in 2011 by one us (MW). Subsequent
58 dedicated field work allowed collecting ~23,000 samples¹ from over 100 discrete locations
59 over a surface of ~650 km² (Fig. 1). The borders of the strewnfield are constrained by sites
60 where a 60 man.minutes search did not reveal a single atacamaite. A few tens of similar-looking
61 glass samples have been found sporadically about 40 km northwest of the strewnfield. The
62 maximum dimension of the strewnfield is therefore at least 100 km. Samples were encountered
63 lying on the desert surface, and more abundant, up to several tens per m², in gravels
64 concentrations. They were encountered on all geological units present in the area. They range
65 from 1 to 35 mm in length, with an average mass of 0.55 ± 0.48 g (1σ), and a maximum mass
66 of 5.9 g. They are pieces of black glass, with minor vesicularity. The vast majority of samples
67 display globular forms, with rare button, dumbbell, or teardrop shapes (Fig. 2A). The average
68 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

69 1.74±0.57 and 1.43±0.30 (n=989). Most pieces show a somewhat dull abraded surface
70 attributed to transport and/or sand blasting. A limited number of samples show a shiny surface
71 with small droplets stuck to the surface, as well as contorted splash-forms.

72

73 **3. Methods**

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

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

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

99 obtained for NBS 987 and La Jolla standards during the course of the study are respectively
100 $^{87}\text{Sr}/^{86}\text{Sr} = 0.710254 \pm 0.000003$ (2σ , $n=8$) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.511830 \pm 0.000003$ (2σ , $n=6$).

101 Quantitative major element analyses were conducted using electron microprobe analyses
102 (EPMA) Cameca SX100 at UPMC CAMPARIS facility. The operating conditions were 15 kV
103 accelerating voltage with a current of 10 nA and a counting time of 30 s, with a focused beam
104 ($1 \mu\text{m}$). Both natural and synthetic standards were used for calibration: albite for Na; anorthite
105 for Al; apatite for P; diopside for Mg, Si, Ca; orthoclase for K; MnTiO_3 for Mn and Ti; Fe_2O_3
106 for Fe; and NiO for Ni. Typical detection limits are (in ppm): 450 for Na, 470 for Al, 710 for
107 Mg, 670 for Si, 610 for Ca, 600 for K, 1040 for Mn, 420 for Ti, 1270 for Fe, and 1330 for Ni.

108 ^{57}Fe Mössbauer spectroscopy (^{57}Fe -MS) was conducted at CBPF, Brazil. It was performed
109 at room temperature (RT) in standard transmission geometry using a 25 mCi $^{57}\text{Co}/\text{Rh}$
110 radioactive source in sinusoidal mode. Spectra were recorded for 96 hours in a 512 channels
111 spectrometer and the drive velocity calibration was taken at room temperature (RT) with an α -
112 Fe foil. All isomer shifts reported in this work are given relative to α -Fe at RT. The error in
113 source velocity is less than 1%. For each studied sample, about 100 mg of material was grinded
114 and used as Mössbauer absorber. Spectral analysis was performed with the two-dimensional
115 extended Voigt-based fitting method (x-VBF) developed by Lagarec and Rancourt (1997). This
116 method provides the total Probability Density Distribution (PDD) of static hyperfine
117 parameters allowing the analysis of independent, partially or fully correlated arbitrary-shape
118 partial distributions of isomer shift (δ), quadrupole splitting (Δ) and, for magnetically ordered
119 materials, hyperfine magnetic Zeeman splitting (z).

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

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

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

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

149

150 **3. Petrography**

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

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

164 The grain density, measured by helium pycnometry on three separate atacamaite batches
165 totaling 67 g, is 2.48 g/cm^3 . The water content estimated by micro infrared spectroscopy is
166 $177 \pm 32 \text{ ppm}$ (19 analyses, on 4 samples).

167

168 **4. Geochemistry**

169 Magnetic susceptibility of atacamaites shows a log normal distribution with a median of 169
170 $10^{-9} \text{ m}^3/\text{kg}$ compatible with a paramagnetic behavior, i.e., iron diluted in the glass (Rochette et
171 al., 2015). Magnetic susceptibility correlates roughly with the bulk Ni content, indicating that
172 it may be a good proxy to select samples with higher extraterrestrial contamination (Rochette
173 et al., 2015). Therefore, in addition to regular samples, we selected specifically samples with
174 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
175 trace elements analyses, and EPMA.

176 Average bulk chemical composition of atacamaites (Table 2) is similar to a K-rich dacite, with
177 $\text{SiO}_2 = 64.1 \text{ wt.}\%$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.54 \text{ wt.}\%$, and $\text{K}_2\text{O} = 2.98 \text{ wt.}\%$ ($n=15$). Iron is extremely
178 heterogeneous ($\text{FeO}_{\text{total}}$ ranges from 4.58 to 14.2 wt.%), and correlates with Ni and Co
179 abundances that are high, up to 4800 ppm and 400 ppm, respectively (Fig. 3). At microscopic
180 scale, EPMA (Table S1) show that the Fe-rich regions are also enriched in Ni, with a good
181 correlation between Ni and Fe contents (Fig. 3a).

182 Chondrite-normalized REE patterns are similar for all samples, characterized by a La_N/Lu_N
183 ratio ranging from 7.47 to 8.00 and a significant negative Eu anomaly ($\text{Eu}/\text{Eu}^*=0.50$),
184 compatible with a dacitic target (Fig. 4). Strontium and Nd isotopic compositions, measured
185 for five samples, also reveal fairly homogeneous isotopic compositions, with $^{87}\text{Sr}/^{86}\text{Sr} = 0.7076$
186 ± 0.0001 and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512636 \pm 0.000006$ (Fig. 5).

187

188 **5. Mössbauer spectroscopy**

189 Five atacamaite samples were studied for Mössbauer spectroscopy. The room temperature ^{57}Fe
190 Mössbauer spectra of all samples were fitted with two components described as distribution 1
191 (D1) and distribution 2 (D2). A typical spectrum is shown in Figure 6a. Only sample J338-23,
192 selected for its high magnetic susceptibility, exhibited a magnetic phase ordered at room
193 temperature, identified as magnetite and fitted with two sextets assigned as Fe-A and Fe-B.
194 The former, with average hyperfine field (B_{hf}) ~ 49 T, corresponds to Fe^{3+} at tetrahedral sites
195 in magnetite while the latter ($B_{\text{hf}} \sim 45$ T) to $\text{Fe}^{2.5+}$ at octahedral sites (Cornell and Schwertmann
196 2003).

197 Despite the differences in relative areas, all samples exhibit similar average hyperfine
198 parameters for D1 and D2 (Table 3). The main distribution D1 presents average isomer shift
199 $\langle\delta\rangle \sim 0.88 - 1.02$ mm/s and average quadrupole splitting $\langle\Delta\rangle \sim 1.95 - 2.19$ mm/s that is
200 usually associated to Fe^{2+} in octahedral coordination, as shown in previous works on tektites
201 and other natural glasses (Dunlap and Sibley 2004; Stewart et al. 2003). However, as pointed
202 out by Rossano et al. (1999), D1 could also be assigned to a five-fold co-ordinated Fe^{2+} . In
203 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
204 likely to be Fe^{3+} in octahedral coordination (Johnson and Johnson 2005). Although previous
205 works on tektites (e.g., Australasian) indicate $\langle\Delta\rangle \sim 0.00$ mm/s for Fe^{3+} (Dunlap and Sibley

206 2004), some impact glasses (e.g., Aouelloul glass, irghizites) show iron species with
207 appreciable quadrupole splitting that is very much Fe^{3+} -like (Dunlap and McGraw 2007). In
208 this sense, the Mössbauer data of atacamaites have much more in common with these impact
209 glasses. Indeed, except for the presence of magnetite in sample J338-23, the shape of all
210 Mössbauer spectra is very similar to the one of Irghizite impact glass (see Fig. 1c, in Dunlap
211 and McGraw 2007).

212 As shown in Fig. 6b and 6c, the isomer shift and quadrupole splitting for D1 and D2 are
213 distributed around their average values, in accordance with the wide range of local distortion
214 of cation environments observed in glasses. As a result, D1 and D2 may contain small
215 contributions due to tetrahedrally coordinated iron (Fe^{2+} or Fe^{3+}), as already identified in
216 silicate glasses (Johnson and Johnson 2005; Stewart et al. 2003). In addition, although the
217 occurrence of electron delocalization has not been reported for previously studied tektites
218 (Rossano et al. 1999), this effect cannot be neglected in our samples - electron delocalization
219 results in average value of isomer shift (0.5 – 0.9 mm/s) that can be assigned to $\text{Fe}^{2.5+}$ (Dyar et
220 al. 2006). Despite this issue concerning the distribution of hyperfine parameters, an estimate
221 for $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio for the studied samples could be determined if D1 and D2 are associated to
222 Fe^{2+} and Fe^{3+} , respectively, based on the average values of hyperfine parameters as previously
223 mentioned. Thus, considering the relative areas for D1 and D2 (Table 3), $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio ranges
224 from 0.282 (for sample PT2d) up to 0.857 (for sample J338-23). $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ can be estimated
225 between 22% (for PT2d) and 36% (for J338-23), taking $\text{Fe}_{\text{total}} = \text{Fe}^{3+} + \text{Fe}^{2+}$. The average
226 $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ ratio is $27.7 \pm 5.4\%$ for the three typical atacamaite samples (i.e. the ones with
227 magnetic susceptibility between 176 and 272 $10^{-9} \text{ m}^3/\text{kg}$, namely JG2h, PT2d, and K51f).
228 These ratios are considerably higher than the ones already reported for tektites from other
229 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;
230 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 atacamaïtes**

240 Petrological and geochemical characteristics of atacamaïtes, 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 atacamaïtes 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 atacamaïtes 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 atacamaïtes (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

254 extraterrestrial impactor rich in Fe, Ni and Co (Fig. 3). Although we do not know the
255 composition of the target, it is necessarily a dacitic rock that has practically no Ni and Co
256 compared to the impactor. Therefore, the Ni/Co ratio of the impactor can be estimated from
257 the Ni/Co ratio of the most impactor-rich atacamaïtes. This ratio, computed for atacamaïtes
258 with Ni content above 2500 ppm is $\text{Ni/Co}=12.0\pm 0.2$ (1σ , $n=5$). The Ni/Co ratio of the impactor
259 (12.0 ± 0.2) is inconsistent with a chondritic projectile characterized by Ni/Co ratios around 21
260 (e.g., Wasson and Kallemeyn, 1988). Similarly, the absence of enrichment in Cr precludes a
261 chondritic impactor (Fig. 3C). Therefore, the geochemical data point to an iron impactor. Under
262 the reasonable assumption that Fe, Ni, and Co are the only significant elements in the impactor
263 and mixing lines as exemplified in Figure 3, the bulk composition of the impactor is estimated
264 to 94.15 wt.% Fe, 5.4 wt.% Ni, 0.45 wt.% Co.

265 The 5.4 wt.% Ni content and the 12.0 Ni/Co ratio of the impactor allow to constrain more
266 precisely the nature of the impactor. The only iron meteorite groups with similar Ni content
267 (<7.5 wt.%) are IC, IIAB, and IIG groups with average Ni contents of 6.50 ± 0.27 wt.% (1σ ,
268 $n=41$ analyses), 5.70 ± 0.33 wt.% ($n=274$), 4.53 ± 0.44 wt.% ($n=18$), respectively (Koblitz, 2005;
269 Gattacceca et al., 2018, Wasson et al., 2007). The average Ni/Co ratio for IC, IIAB, and IIG
270 meteorites are 14.17 ± 0.68 ($n=20$), 12.41 ± 0.75 ($n=156$), 8.97 ± 0.79 ($n=8$), respectively (Koblitz,
271 2005; Gattacceca et al., 2018; Wasson et al., 2007). The best fit is clearly with IIAB meteorites.
272 In particular, no IC meteorite has $\text{Ni/Co}<13.4$, and no IIG meteorite has $\text{Ni/Co}>10.8$. Only two
273 meteorites from of the IAB complex, out of 537 analyses, have Ni content below 6 wt.%, and
274 only 5, out of 326 analyses, have $\text{Ni/Co}<13$ (Koblitz, 2005). Therefore, this group is not
275 considered as a candidate impactor for the atacamaïtes. In conclusion, the IIAB iron group is
276 the most likely candidate for the impactor that formed the atacamaïtes.

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

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

282

283 7.3. Nomenclature and petrogenesis

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

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

292 The redox state of Fe determined by Mössbauer spectroscopy in 5 samples, including two very
293 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
294 three typical samples). This $\text{Fe}^{3+}/\text{Fe}_{\text{total}}$ ratio of $27.7\pm 5.4\%$ show that atacamaites are also much
295 more oxidized than tektites whose oxidation ratios are near zero (Table 1). Atacamaites contain
296 Fe oxides inclusions more frequently than tektites where their occurrence is extremely rare. As
297 a consequence, they are more magnetic than tektites, and their magnetic properties are more
298 variable, especially for small specimens (Rochette et al., 2015).

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

303 Glass with crude splash-forms is also found over limited areas on the rims of the 390 m-
304 diameter Aouelloul crater (Koeberl et al., 1998). Centimeter-sized splash-form glasses are
305 found over a much wider area (~400 km²) around the 1.2 km-diameter Darwin crater (Taylor
306 and Solomon, 1962; Howard, 2009). The impact glasses with closest similarity to atacamaites
307 are irghizites, associated with the 14 km-diameter Zhamanshin crater in Kazakhstan (Bouska
308 et al., 1981). Irghizites and atacamaites share similar morphologies (including presence of
309 small attached spherules, Fig. 2a), and important contamination by the impactor (Schulz et al.,
310 2020). A significant difference is the extent of the strewnfield (1-2 km² for irghizites vs. 650
311 km² for Atacamaites).

312 This inventory of tektites and other splash-form impact glasses (Table 1) confirms that it is
313 necessary to combine a number of criteria to discriminate the two categories (following
314 Koeberl, 1994). Chemical homogeneity is a tektite attribute, but it is hard to quantify this
315 homogeneity, and tektites may be heterogeneous (e.g., North American ones, see Albin et al.,
316 2000, and Muong Nong tektites, see Koeberl, 1992). Water content may be ambiguous as non-
317 tektite glasses can be as dry as tektites (Table 1). The reduced character is not exclusive as
318 well, as the Darwin glass is as reduced as tektites (e.g., Rochette et al. 2015). Another criterion
319 may be the distance from the crater that is at least an order of magnitude higher for tektites, but
320 this criterion cannot be strictly applied when the crater location is unknown. A final criterion
321 is crater size, with tektites being associated to craters larger than 10 km. Both criteria cannot
322 be used when the crater is missing, as for atacamaites. In fact, the only other cases of
323 macroscopic non tektite impact glasses without known source crater are Libyan desert glass
324 (e.g., Barrat et al., 1997), and urengoites (e.g., Deutsch et al., 1997), two glasses for which
325 splashforms are not established. The smaller size range (the largest atacamaites are about the
326 size of the smallest tektites) as well as presence of contorted shapes seems to be good criteria
327 for non-tektite material. In addition to the oxidized character and the high impactor

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

330 *7.4. Source impact crater*

331 Considering our fission track age for the atacamaites (7.83 ± 0.26 Ma) compared to erosion rates
332 < 1 m/Ma measured in the hyper-arid part of the Atacama Desert (e.g., Dunai et al., 2005), a
333 ~ 10 km diameter (Zhamanshin size) crater and the associated ~ 400 m deep depression should
334 still be visible in the field and on satellite images. On the other hand, published erosion rates
335 were obtained on surfaces specially selected for their stable morphology. Areas with steep
336 slope or low relative altitude may have higher erosion rates or may have accumulated post 8
337 Ma sediments. Search for impact breccia or non-ejected impact glass were also inconclusive
338 despite several weeks of field work. The failure to detect a candidate source crater for
339 atacamaites suggests it may have been much smaller than 10 km, in the size range of Darwin
340 crater (1.2 km diameter) that produced a ~ 400 km² strewnfield with $\sim 15\%$ of splash-form
341 (Howard, 2009). Modeling shows that cm-sized particles for such small craters can indeed be
342 ejected for several tens of km (Shuvalov and Dypvik, 2013). Finding such delicate glass ejecta
343 present at the surface of Atacama Desert since nearly 8 Ma points toward the extreme stability
344 of Atacama Desert surfaces, already demonstrated by elevated cosmogenic nuclide contents
345 (Dunai et al., 2015), high meteorite densities (Hutzler et al., 2007), and old meteorite terrestrial
346 ages (Drouard et al., 2019).

347

348 **8. Conclusions**

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

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

365

366 **ACKNOWLEDGMENTS**

367 We thank Luigi Folco and an anonymous reviewer for their useful and constructive comments
368 that helped improve this manuscript. This project was funded by the Programme National de
369 Planétologie (INSU/CNES), and FONDECYT (3140562). BR acknowledges financial support
370 of the LABEX Lyon Institute of Origins (ANR-10-LABX-0066) of the Université de Lyon
371 within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) of the French
372 government operated by the National Research Agency (ANR). The national Raman facility at
373 ENS de Lyon is supported by INSU.

374

375 **FIGURE CAPTIONS**

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

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

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

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

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

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

396

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

	Fe ³⁺ /Fe _{total}	water (ppm)	magnetic susceptibility (10 ⁻⁹ m ³ /kg)		maximum distance from crater (km)	crater diameter (km)	age (Ma)	impactor
			mean±SD	range				
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.

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

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

574

575

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

Samples	D1			D2			Magnetite								Area ratio D2/D1	
	$\langle\delta\rangle$ (mm/s)	$\langle\Delta\rangle$ (mm/s)	A (%)	$\langle\delta\rangle$ (mm/s)	$\langle\Delta\rangle$ (mm/s)	A (%)	Fe-A				Fe-B					
							$\langle\delta\rangle$ (mm/s)	$\langle\Delta\rangle$ (mm/s)	$\langle B_{\text{hf}}\rangle$ (T)	A (%)	$\langle\delta\rangle$ (mm/s)	$\langle\Delta\rangle$ (mm/s)	$\langle B_{\text{hf}}\rangle$ (T)	A (%)		
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

577

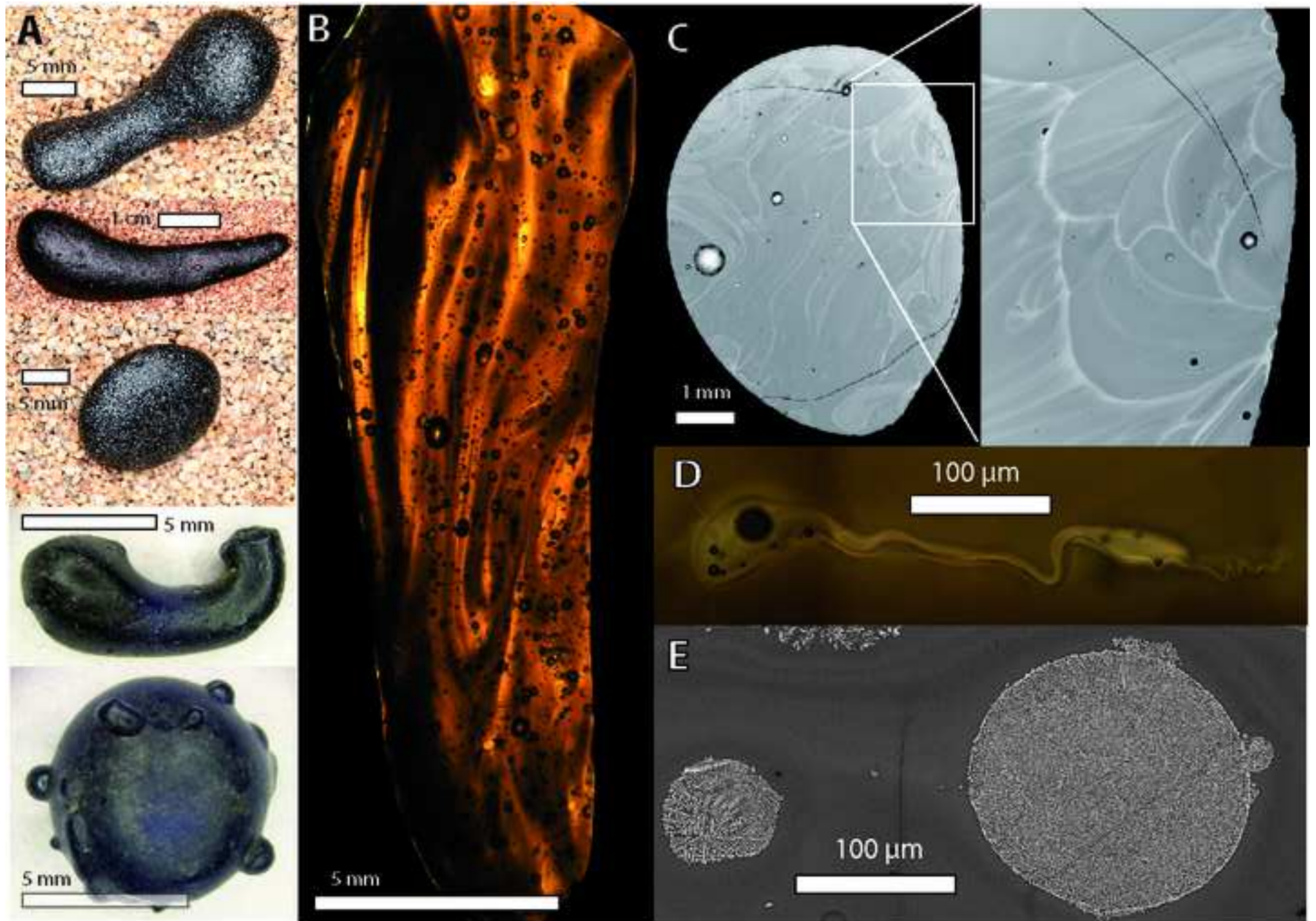
578
579 $\langle\delta\rangle$: mean isomer shift relative to alpha-iron, $\langle\Delta\rangle$: mean quadrupole splitting, $\langle B_{\text{hf}}\rangle$: mean
580 hyperfine field, A: relative area. The Gaussian widths for the center shift (σ_{δ}) and quadrupole
581 splitting (σ_{Δ}) distributions 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 $\langle\delta\rangle$, $\langle\Delta\rangle$, and $\langle B_{\text{hf}}\rangle$ are ± 2 for the last
584 digit. For relative area, uncertainty is $\pm 1\%$.

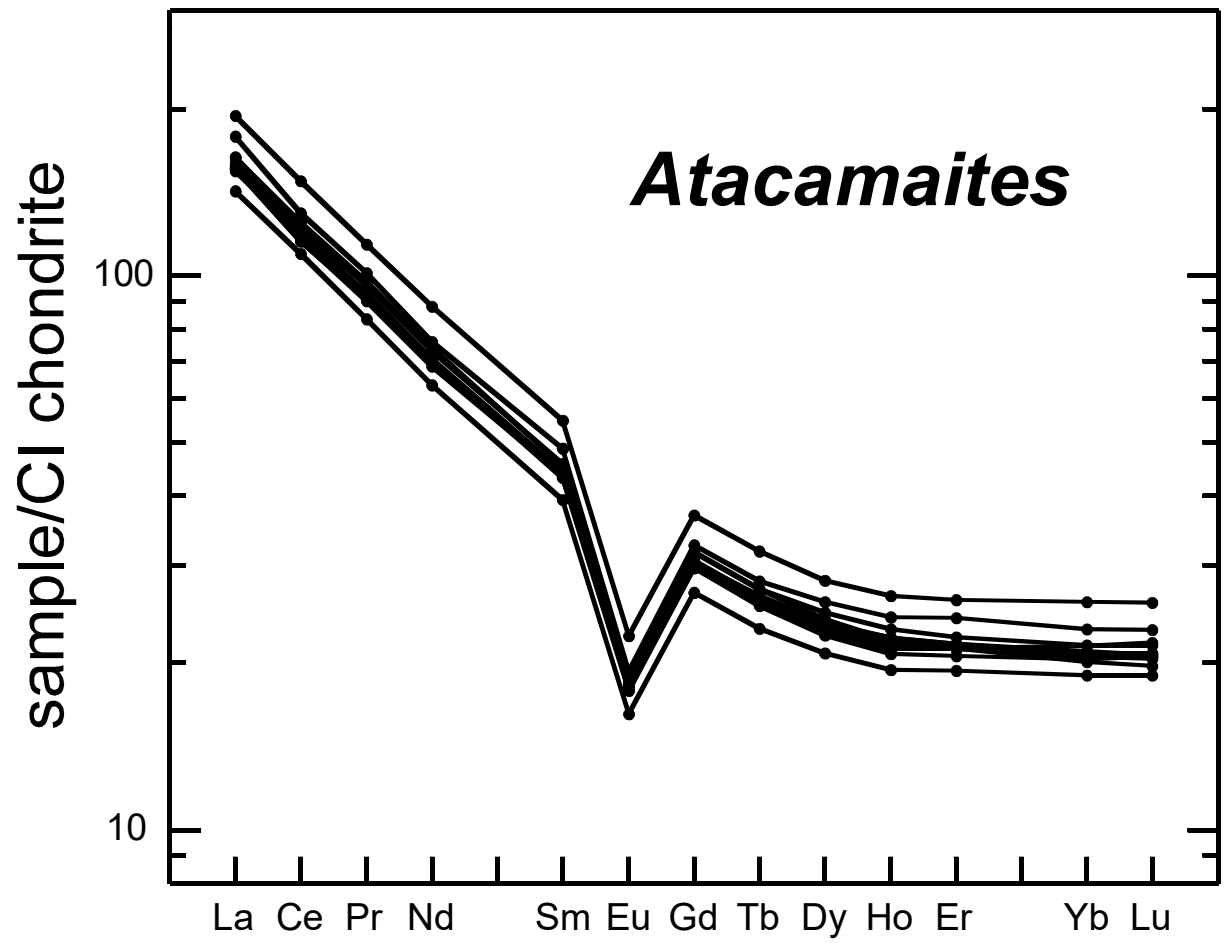
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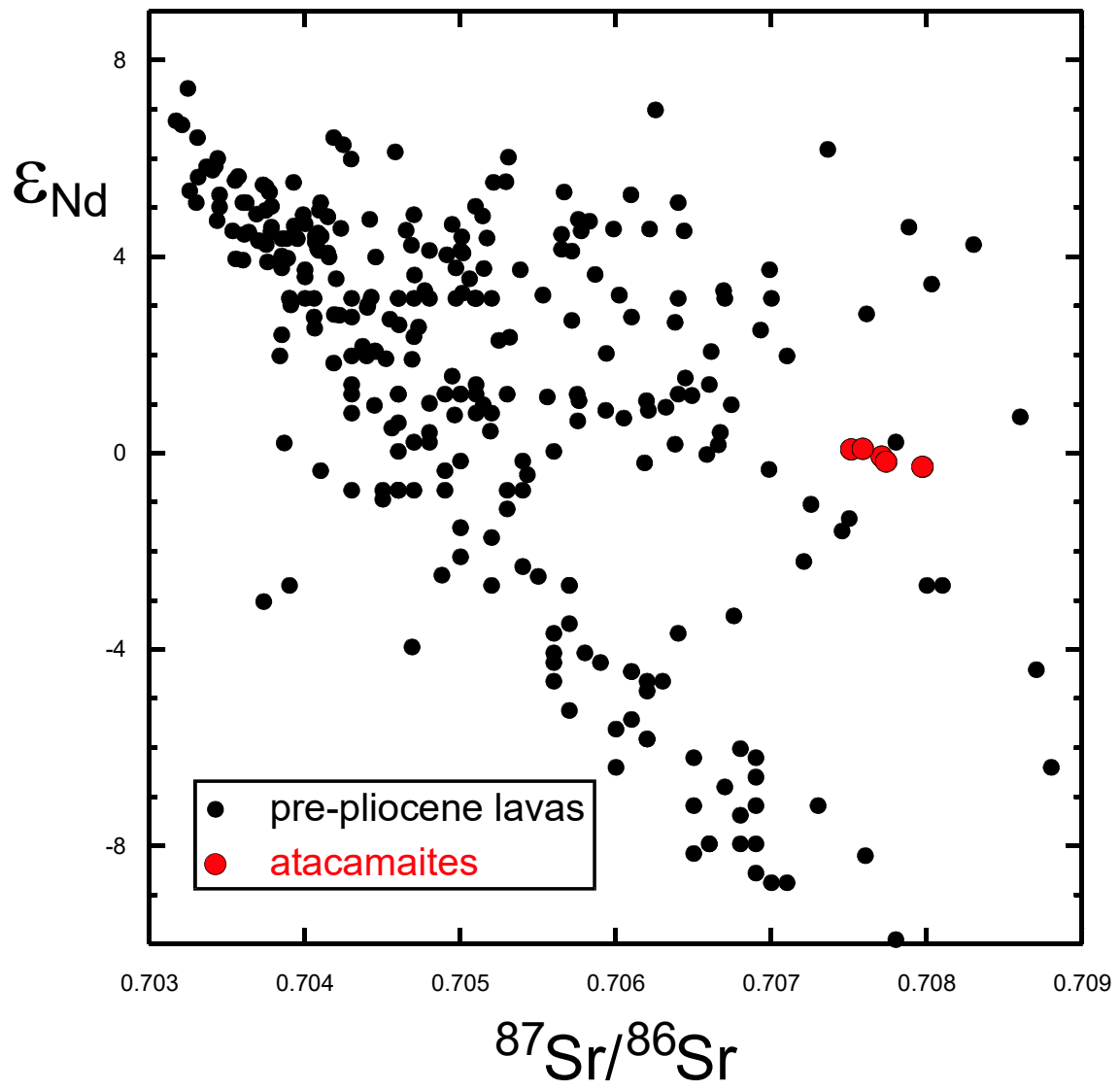
586 **Table 4.** Fission-track dating

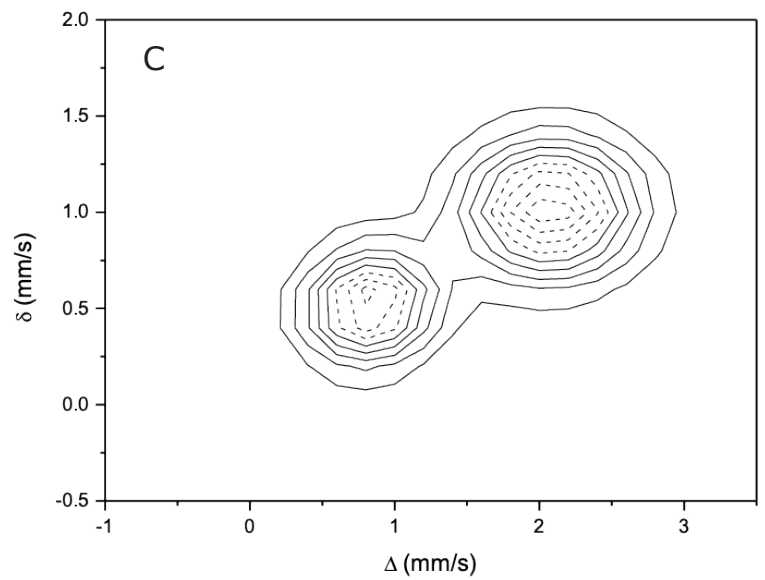
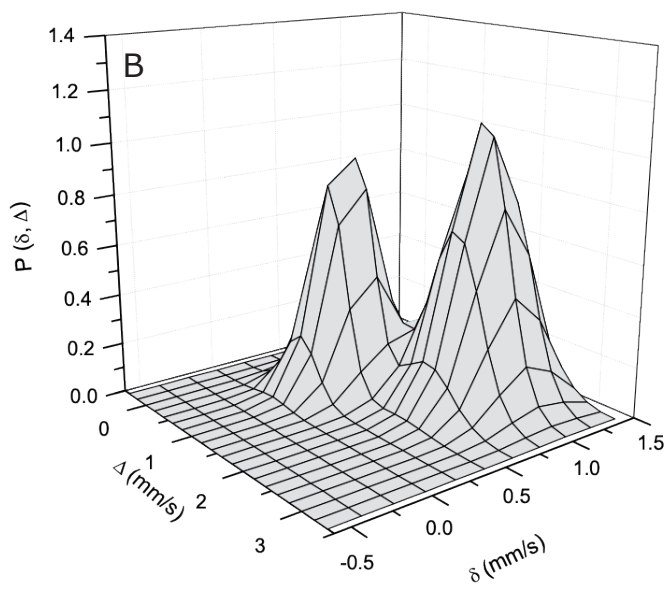
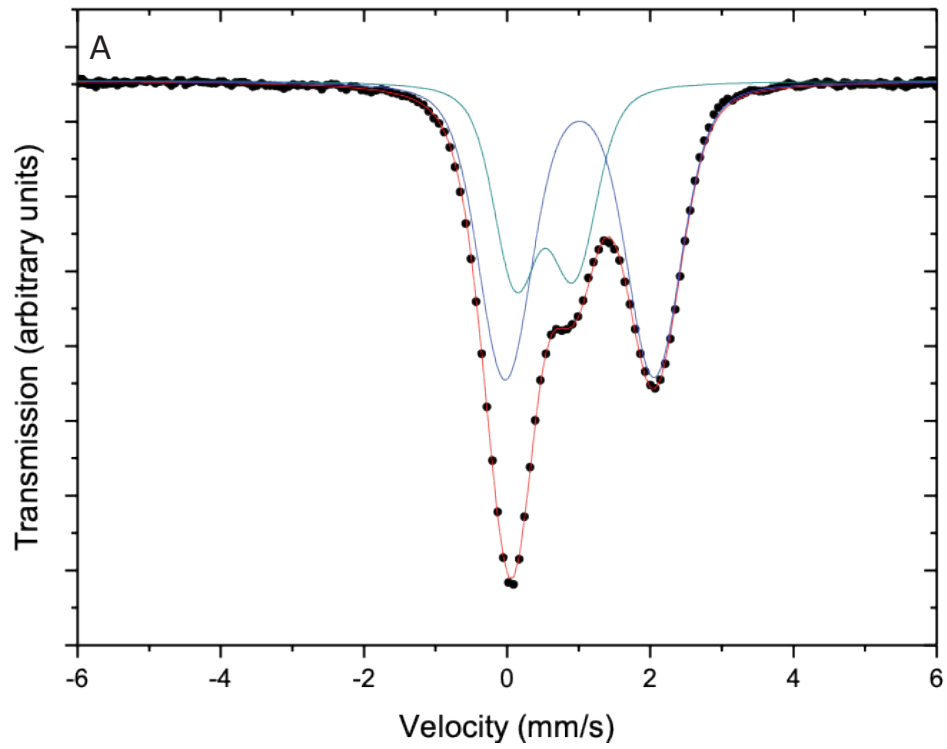
Sample	Heating	ρ_s (cm^{-2})	n_s	ρ_i (cm^{-2})	n_i	$p(\chi^2)$ (%)	D_s/D_i	Age ($\pm 1\sigma$) (Ma)
JG26	Ambient	1990	66	183000	1071	66	0.72	3.42 ± 0.43
	4h 220°C	1400	282	54700	1084	7	1.01	8.08 ± 0.54
PT7E	Ambient	2370	329	177000	1041	99	0.83	4.20 ± 0.27
	4h 220°C	1680	260	70100	1108	60	0.97	7.57 ±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

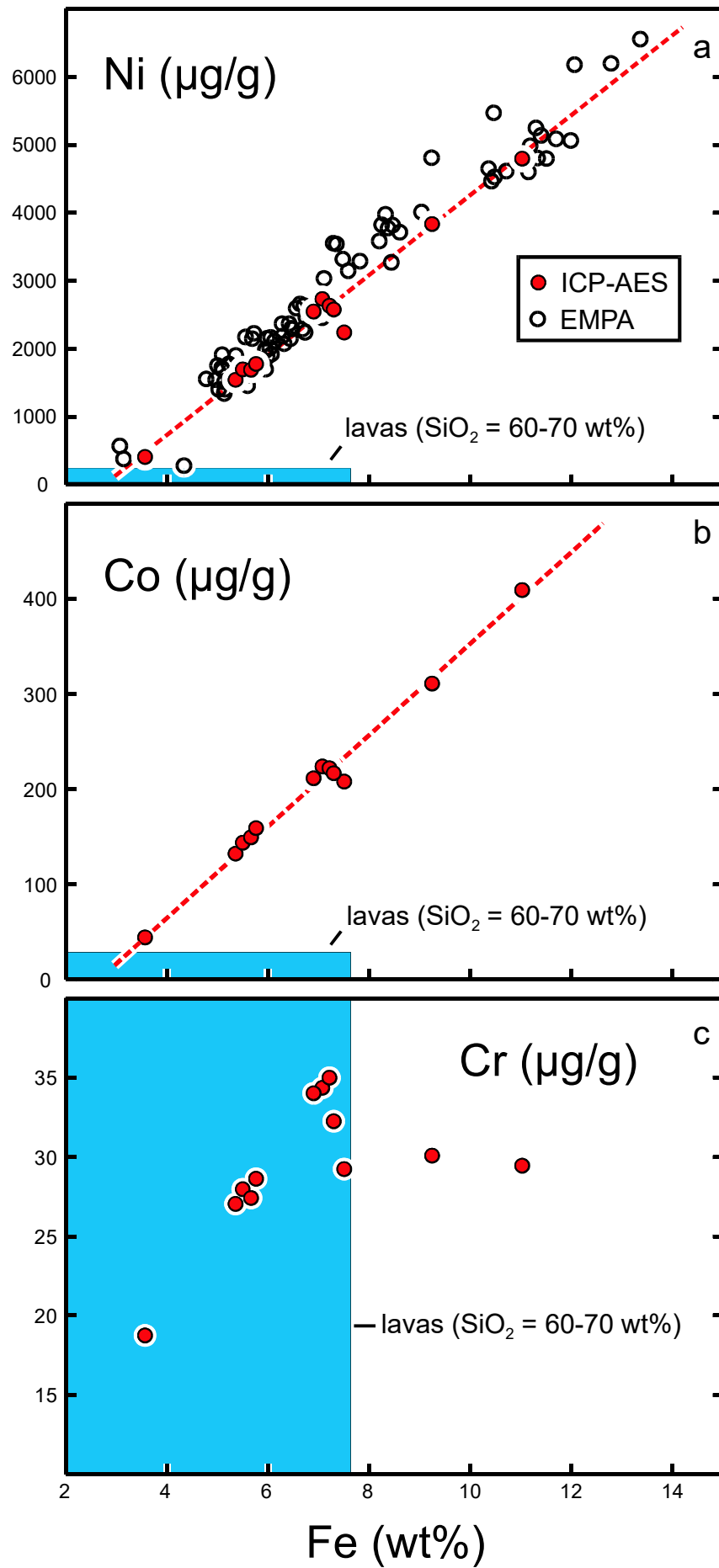
587 Heating: Thermal treatment imposed for plateau age determination; ρ_s (ρ_i): spontaneous
588 (induced) track density; n_s (n_i): spontaneous (induced) tracks counted; $p(\chi^2)$: probability of
589 obtaining χ^2 value testing induced track counts against a Poisson distribution; D_s/D_i :
590 spontaneous 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.

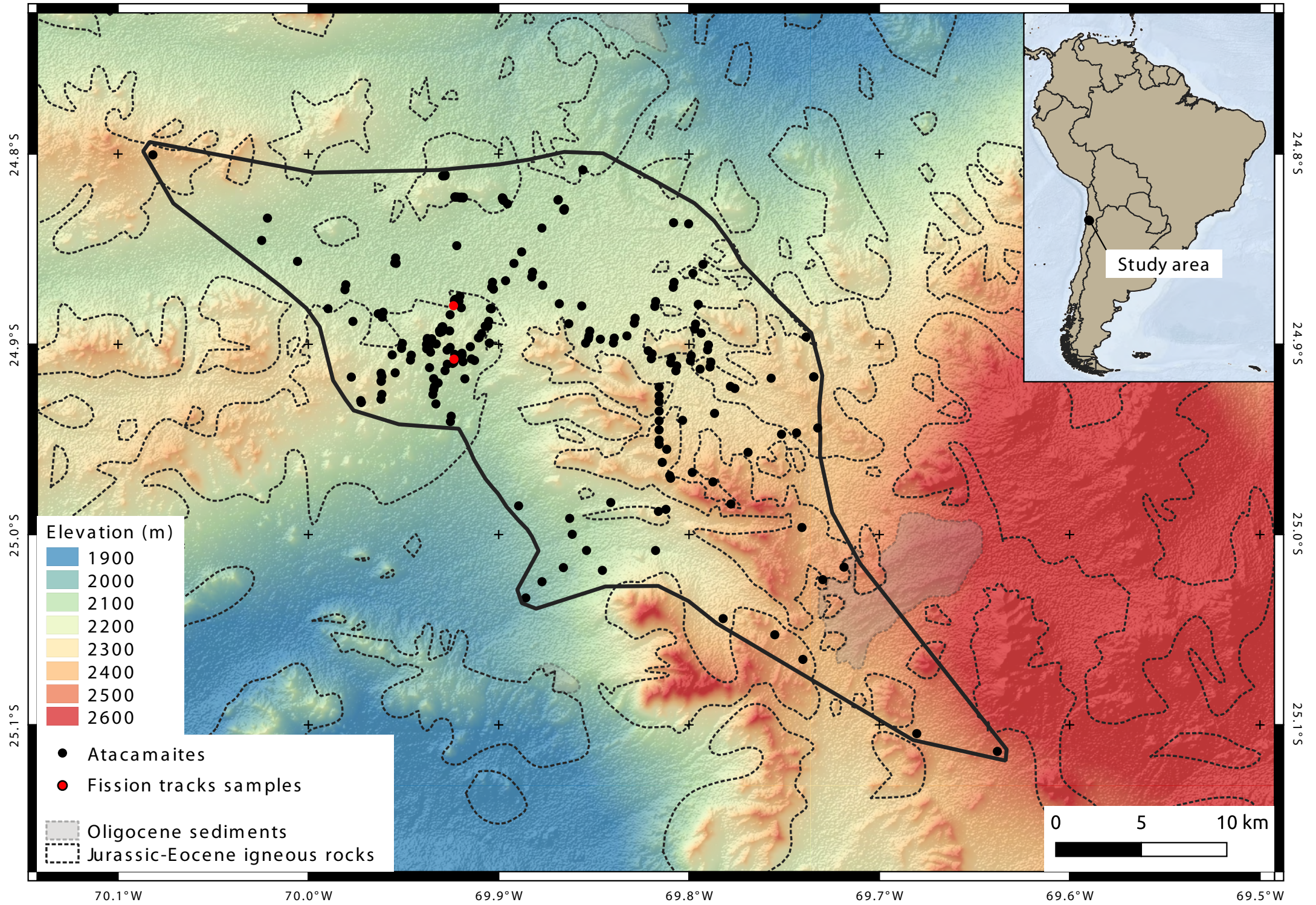














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Figure 01 revised.pdf





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