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Tissint Martian Meteorite: A Fresh Look at the Interior, Surface, and Atmosphere of Mars

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Tissint (Morocco) is the fifth Martian meteorite collected after it was witnessed falling to Earth. Our integrated mineralogical, petrological and geochemical study shows that it is a depleted picritic shergottite similar to EETA79001A. Highly magnesian olivine and abundant glass containing Martian atmosphere are present in Tissint. Refractory trace element, S and F data for the matrix and glass veins in the meteorite indicate the presence of a Martian surface component. Thus, the influence of in situ Martian weathering can be unambiguously distinguished from terrestrial contamination in this meteorite. Martian weathering features in Tissint are compatible with the results of spacecraft observations of Mars. Tissint has a cosmic ray exposure age of 0.7 ± 0.3 Ma, consistent with those of many other shergottites, notably EETA79001, suggesting that they were ejected from Mars during the same event.

Demonstration in the early 1980s that an important group of meteorites was of Martian origin represented a breakthrough in attempts to understand the geological evolution of Mars (1–3). Unfortunately, most of the samples were collected long after their arrival on Earth and thus have experienced variable degrees of terrestrial weathering (4). Even the few Martian meteorites that were collected shortly after their observed fall to Earth have been exposed to organic and other potential contaminants during storage. Here we report on the Tissint Martian meteorite, which fell on 18th July 2011 in Morocco (figs. S1 and S2). This is only the fifth witnessed fall of a meteorite from Mars and therefore provides an opportunity to improve our understanding of processes that operated on that planet at the time the meteorite was ejected from its surface.

The largest recovered stones from the Tissint fall are almost fully covered with a shiny black fusion crust (Fig. 1). Internally the meteorite consists of olivine macrocrysts set in a fine-grained matrix of pyroxene and feldspathic glass (maskelynite) (5) (figs. S3 to S6, tables S1 to S6). The matrix is highly fractured and penetrated by numerous dark shock veins and patches filled with black glassy material enclosing bubbles (fig. S7). The petrology of Tissint shows similarities to other picritic shergottites (an important group of olivine-rich Martian basaltic rocks),

in particular, lithologies A and C of EETA79001 (2). The grain density and magnetic properties of Tissint (fig. S8) also match previous results from basaltic and picritic shergottites (6).

Tissint is an Al-poor ferroan basaltic rock, rich in MgO and other compatible elements (Ni, Cr, Co). Its major element abundances are similar to those of the other picritic shergottites, especially EETA79001. Furthermore, key element ratios (wt%/wt%) such as FeO/MnO (39.7), Al/Ti (7.2), Na/Ti (1.41), Ga/Al (3.9×10^{-3}), Na/Al (0.20) (3, 4, 14) and $\Delta^{17}\text{O}$ (+0.301‰) (fig. S9) (7) are also typical of Martian meteorites. The average composition of the black glass (tables S7 and S8) is identical to a mixture of the major phases of the rock (augite, maskelynite and olivine: 50:20:30) with compositional variations reflecting incomplete dissolution of one phase or another (fig. S7). Among minor elements in the black glass, chlorine is always below the detection level of EMPA (100 ppm), whereas fluorine and sulfur exhibit variations in the range 0–4000 ppm and 0–6000 ppm respectively (5).

Like most other picritic shergottites, bulk Tissint displays a marked depletion in light rare earth elements (LREE) and other highly incompatible elements, such as Rb, Li, Be, Nb, Ta, Th and U (Fig. 2). Its Lu/Hf ratio (0.2) is in the range of values measured for EETA79001 and other basaltic shergottites (0.1 to 0.2, e.g., (8)), and lower than those of the picritic shergottites DaG 476/489, SaU 005 and Dhofar 019 (about 0.3, (9–11)). Although the sizes of the two samples analyzed here are somewhat

limited (0.49 g and 1.25 g), their trace element abundances are very similar and so are likely to be representative of the whole rock composition, despite the irregular distribution of olivine megacrysts.

In order to evaluate the possible heterogeneity of this stone, we analyzed two additional samples: a groundmass-rich sample (devoid of large olivine crystals, and weighing 181 mg) and a fragment of the same glassy pocket selected for volatile analysis (40 mg). Both samples display markedly higher LREE abundances, with REE patterns generally similar to those of the enriched shergottites, as exemplified by Zagami. However, there is a minor, but analytically valid, positive Ce anomaly (Ce/Ce* = 1.1) (Fig. 2) and the La/Nd, La/Nb and Th/La ratios are higher than those of other enriched shergottites (fig. S10). These two samples indicate that a LREE-enriched component, different from those previously recorded in other shergottites, is heterogeneously dispersed throughout the matrix of Tissint.

The presence of short-lived ⁴⁸V ($T_{1/2}$ = 16 days), among other cosmogenic isotopes, demonstrates that the stones we analyzed are from the fall of July 18th (table S10). We measured stable cosmogenic isotopes of He, Ne and Ar in three aliquots, consisting of matrix-rich, glass-matrix mixed, and glass-rich separates (table S11). The Cosmic Ray



Fig. 1. The Natural History Museum (London) stone. This 1.1 kg stone (BM.2012,M1) exhibits a black fusion crust with glossy olivines. The olivine macrocrysts (pale green) and the numerous black glass pockets and veins, are characteristics of this shergottite. The scale is in cm.

Exposure ages (CRE ages) computed for $^3\text{He}_c$, $^{21}\text{Ne}_c$, and $^{38}\text{Ar}_c$ are 1.2 ± 0.4 , 0.6 ± 0.2 and 0.9 ± 0.4 Ma respectively, resulting in an average CRE age of 0.7 ± 0.3 Ma for Tissint. This age is in the range of CRE ages of other shergottites, notably that of EETA79001 (0.73 ± 0.15 Ma (2)), suggesting that Tissint and other shergottites were ejected during a single event. Nitrogen isotopes were analyzed together with the noble gases. The glass aliquot displayed a well-defined excess of ^{15}N , which persisted after correction for contribution of cosmogenic $^{15}\text{N}_c$ (assuming a production rate of $6.7 \pm 2.6 \times 10^{-13}$ mol $^{15}\text{N}/\text{gMa}$) (12). This excess ^{15}N is best explained by trapping of a Martian atmospheric component (2). Using a $\delta^{15}\text{N}$ versus $^{40}\text{Ar}/\text{N}$ correlation and taking a Martian atmospheric value from the Viking measurements, of 0.33 ± 0.03 (13), we obtain a $\delta^{15}\text{N}$ value of 634 ± 60 ‰ (1 σ), which agrees well with the Viking measurement of 620 ± 160 ‰ (14) (Fig. 3).

Simultaneous measurement of carbon and nitrogen was carried out by stepped combustion-mass spectrometry on a small chip (21 mg) from the same sample we used for oxygen isotopic analysis (5). The sample had a total carbon abundance of 173 ppm and $\delta^{13}\text{C}$ of -26.6 ‰, and contained 12.7 ppm nitrogen with total $\delta^{15}\text{N}$ of -4.5 ‰. At temperatures above 600°C , both carbon and nitrogen were distributed between 3 discrete Martian components (fig. S11, table S12). Below 600°C , readily-resolvable components of organic material combusted; while these may have been introduced during post-fall collection and sample storage, and are an unavoidable consequence of sample handling procedures, we cannot yet rule out the presence of small quantities of indigenous Martian organic matter (5). At the highest temperatures of the extraction, there was a clear indication of the presence of trapped Martian atmosphere, with elevated $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (even allowing for a cosmogenic component, blank-corrected $\delta^{13}\text{C}$ reaches $+16$ ‰ and $\delta^{15}\text{N}$ reaches $+298 \pm 25$ ‰). At intermediate temperatures ($600 - 800^\circ\text{C}$), there were maxima in both $\delta^{13}\text{C}$ (-14 ‰) and $\delta^{15}\text{N}$ ($+110$ ‰), suggesting that the component bears some relationship to the Martian atmosphere. In addition, there was clear analytical evidence for a simultaneous release of sulfur (~ 19 ppm), presumably from either sulphide or sulfate decomposition.

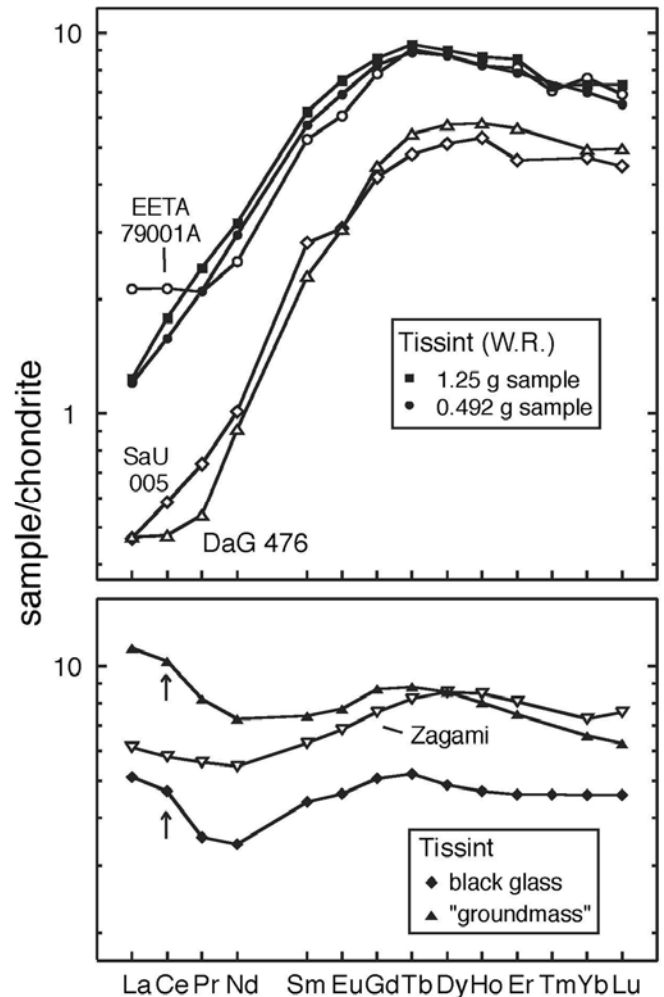


Fig. 2. REE patterns: Top: Tissint in comparison with other depleted picritic shergottites. Bottom: Black glass and groundmass-rich fraction in comparison with enriched shergottite Zagami. Data from (9-11). CI chondrite normalization values are from (24).

This intermediate component probably corresponds to a surface-derived weathering component, as identified in Tissint glass on the basis of REE, S and F data (see below). The third Martian component represents magmatic carbon, which is present in low abundance (1.4 ppm with $\delta^{13}\text{C}$ of -26.3 ‰) and is associated with isotopically-light nitrogen ($\delta^{15}\text{N} < +10$ ‰).

Our study demonstrates that Tissint is a picritic shergottite comparable in many respects to EETA79001. The black shock glass resembles lithology C of EETA79001, as well as shock melt pockets commonly found in other shergottites (15). Major elements and oxygen isotope data indicate that this glass represents a melted mixture of the surrounding bulk rock, composed of olivine, maskelynite and clinopyroxene (5). However, this glass is substantially different from the bulk meteorite and igneous groundmass in that it has a variable, but generally high S and F content; a distinct LREE-enriched composition; and a high $\delta^{15}\text{N}$ value indicative of trapped Martian atmosphere.

The LREE-enriched composition of the glass is somewhat enigmatic. Phosphates are often invoked as a carrier of REE. However, the P content of the black glass relative to bulk rock is not consistent with

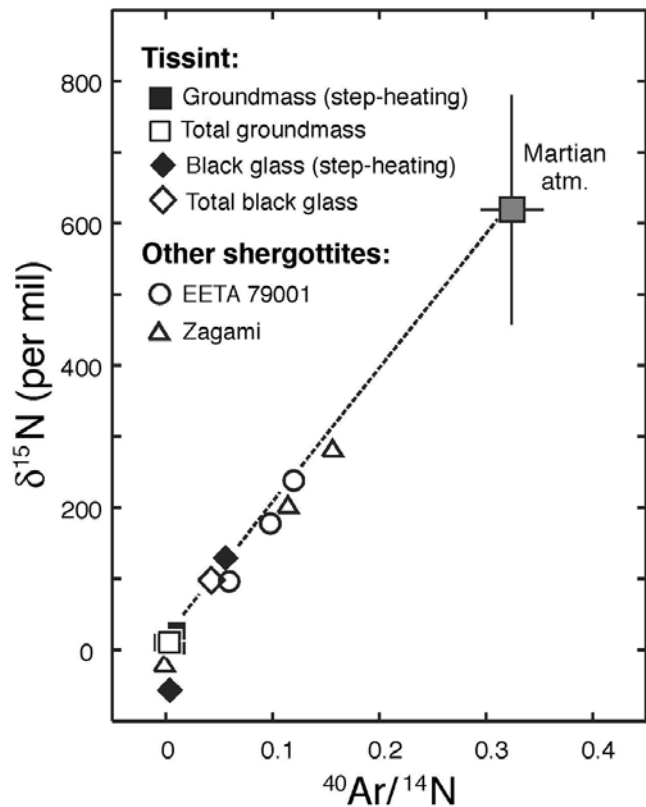


Fig. 3. Gas analyses of the black glass. Both bulk analyses and step heating analyses plot on a single mixing line between terrestrial atmospheric gas (at left) and Mars atmospheric gas (13), Zagami data from (25).

enrichment in phosphates. One possibility to explain the LREE composition of the glass might be selective crustal contamination prior to final emplacement of the Tissint magma. Although LREE-enriched magmatic rocks have been generated on Mars, as exemplified by the Nakhilites and Chassignites, these do not exhibit anomalous Ce abundances (16, 17). In addition, crustal contamination of magma is unlikely to result in REE ratio variations at the sub-centimeter scale, as observed here. Decoupling of Ce from the other REE, indicates partial oxidation to Ce^{4+} , a process that requires oxidising conditions, such as those that prevail in the near-surface environment of Mars. Surface weathering caused by leaching of phosphates by acid aqueous fluids, the process that is responsible for terrestrial alteration of eucritic meteorites in Antarctica (18), would also explain the LREE-enriched composition of the Tissint glass. The high $\delta^{15}N$ value of the Tissint glass, as well as its enrichment in S and F, demonstrates that it has been contaminated by Martian surface components. In view of this evidence, the most likely explanation for the relatively LREE-enriched composition of the glass, and the origin of the Ce anomaly, is that these features also reflect the presence of a near-surface Martian component in Tissint. A Martian soil component was previously suggested for EETA79001 lithology C, which also contains Martian atmospheric gases (19). However, because this meteorite is a find, rather than a fresh fall like Tissint, there's the possibility of terrestrial contamination, which complicates the interpretation (20).

We propose the following scenario in order to explain the composite nature of Tissint. A picritic basalt was emplaced at or near the surface of Mars. After some period, the rock was weathered by fluids, which had leached elements from the Martian regolith. Subsequently, these fluids

deposited mineral phases within fissures and cracks. The Martian weathering products are the most likely source of the required LREE, incompatible and volatile elements. Upon impact, preferential, shock-induced melting occurred in the target rock along fractures where weathering products were concentrated. This melting produced the black glass and retained in it chemical signatures characteristic of the Martian surface. Shock melting also trapped a component derived from the Martian atmosphere, as revealed by stepped combustion-mass spectrometry. About 0.7 Ma ago, the sample was ejected from Mars and eventually landed on Earth in July 2011. The Martian weathering features in Tissint described here are compatible with spacecraft observations on Mars, including those made by the NASA Viking landers, MER Spirit rover and ESA's Mars Express orbiter (5, 21–23).

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