Sm-Nd AND Rb-Sr ISOTOPIC SYSTEMATICS OF A HEAVILY SHOCKED MARTIAN METEORITE TISSINT AND PETROGENESIS OF DEPLETED SHERGOTTITES.

C.-Y. Shih[1], L. E. Nyquist[2], J. Park[3,4] and Carl B. Agee[5] [1]Jacobs, NASA Johnson Space Center, Mail Code JE-23, 2101 NASA Pkwy, Houston, TX 77058, USA, chi-yu.shih-1@nasa.gov; [2]Mail Code KR, NASA Johnson Space Center, Houston, TX 77058-3696, laurence.e.nyquist@nasa.gov; [3]Lunar Planet. Inst., Houston, TX 77058, [4]Dept Chem. & Chem. Biol., Rutgers Univ., Piscataway, NJ 08854, [5]Institute of Meteoritics and Dept. Earth and Planetary Sciences, Univ. New Mexico, Albuquerque, NM 87131.

Introduction: Tissint is a very fresh Martian meteorite that fell near the town of Tissint in Morocco on July 18, 2011. It contains abundant olivine megacrysts (~23%) in a fine-grained matrix of pyroxene (~55%), maskelynitized plagioclase (~15%), opaques (~4%) and melt pockets (~3%) and is petrographically similar to lithologies A and C of picritic shergottite EETA 79001 [1,2]. The presence of 2 types of shock-induced glasses and all 7 high-pressure mineral phases that were ever found in melt pockets of Martian meteorites suggests it underwent an intensive shock metamorphism of ~25 GPa and ~2000°C localized in melt pockets [2]. Mineral textures suggest that olivines, pyroxenes and plagioclases probably did not experience such high-temperature. Earlier determinations of its age yielded 596±23 Ma [3] and 616±67 Ma [4], respectively, for the Sm-Nd system and 583±86 Ma for the Lu-Hf system [4], in agreement with the 575±18 Ma age of the oldest olivine-phyric depleted shergottite Dho019 [5]. However, the exposure ages of Tissint (~1 Ma [1, 6, 7]) and Dho 019 (~20 Ma [8]) are very different requiring two separate ejection events. These previously determined Sm-Nd and Lu-Hf ages are older than the Ar-Ar maskelynite plateau age of 524±15 Ma [9], reversing the pattern usually observed for Martian meteorites. In order to clarify these age issues and place models for Tissint's petrogenesis on a firm basis, we present new Rb-Sr and Sm-Nd isotopic results for Tissint, and discuss (a) the shock effects on them and the Ar-Ar chronometer, (b) correlation of the determined ages with those of other depleted shergottites, and (c) the petrogenesis of depleted shergottites. Since the meteorite is a recent fall, terrestrial contamination is expected to be minimal, but, the strong shock metamorphism might be expected to compromise the equilibrium of the isotopic systems.

Samples and Analytical Procedures: Many small interior fragments of Tissint and one chunk with fusion crust, weighing a total of ~2.5 g was allocated for this study. After chipping off fusion crust fragments, the sample was crushed gently to pass a nylon sieve of opening size <149 μm. About 400 mg was taken as the bulk rock sample (WR). The rest of the sample was sieved into 74-149 μm and 44-74 μm size fractions. Mineral samples were separated from the 74-149 μm size fraction. The non-magnetic plagioclase (Plag) and the most magnetic opaques (MM) were separated by a Franz magnetic separator at a current of 0.8 A. Two more plagioclase samples, 3 pyroxene samples (Px) and 1 olivine sample (Ol) were further separated using combinations of magnetic susceptibilities and densities. In addition, the bulk rock (WR) and all mineral samples except MM were washed with HCl (1N for Plag and Ol and 2N for WR and Px) in an ultrasonic bath for 10 minutes to eliminate possible post-crystallization, extra-terrestrial, or terrestrial, contamination. Residues(r) of acid-washed bulk rock and mineral samples, WR leaches (l) and the combined acid washes from all minerals (Leach) were analyzed.

Sm-Nd isotopic results: Fig. 1 shows $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ data for fifteen Tissint samples (red circles). All fifteen data points define a linear array (blue line) corresponding to a Sm-Nd age of 472±36 Ma for $\lambda(^{147}Sm)=0.00654\ Ga^{-1}$ and an initial $\varepsilon_{Nd}=+44.4\pm1.0$ using the Isoplot regression routines [10]. The data deviate from the isochron by <1.5 ε-unit (see inset). The deviations probably are caused by the heavy shock metamorphism that the meteorite experienced [2]. This age agrees with those of DaG476/Y980459 (470±12 Ma [11,12]) and SaU 094/005 (445±18 Ma [13]), but is significantly younger than the earlier ages reported by [3,4] for Tissint and by [5] for Dho 019. This younger age is also in marginal agreement with the Ar-Ar plateau age (524±15 Ma) for maskelynite grains [9] and the Rb-Sr isochron age (next section) and represents the crystallization age of Tissint. The proposed old ~4.3 Ga Pb-Pb model age for depleted shergottites and Tissint [14], does not agree with our Sm-Nd isotopic data. Simply put, the initial ε_{Nd} values calculated for Tissint at the presumed old age are unreasonably low, e.g., -40 for Leach (phosphates) to -190 for pyroxenes (most resistant mineral). Concordant Sm-Nd, Ar-Ar and Rb-Sr ages for a less shocked Martian shergottite, NWA 1460, also were previously interpreted as a crystallization age (346±17 Ma) [15]. Initial ε_{Nd} and ages for seven depleted shergottites studied so far are summarized in Fig. 2. The figure clearly shows that at least four igneous events related to the formation of depleted shergottites are identified from five or six isotopically distinct sources of super-chondritic $^{147}Sm/^{144}Nd$ (0.264-0.283, blue dotted lines, red line for Tissint). The magmatic activities spanned ~250 Ma. Variable exposure ages for these meteorites suggest that they came from at least four impact-ejection events. Tissint, along with DaG476, SaU005/094, and Y980459 could be derived from a basaltic complex of ~472 Ma old terrane on Mars by a single ejection event ~1 Ma ago.

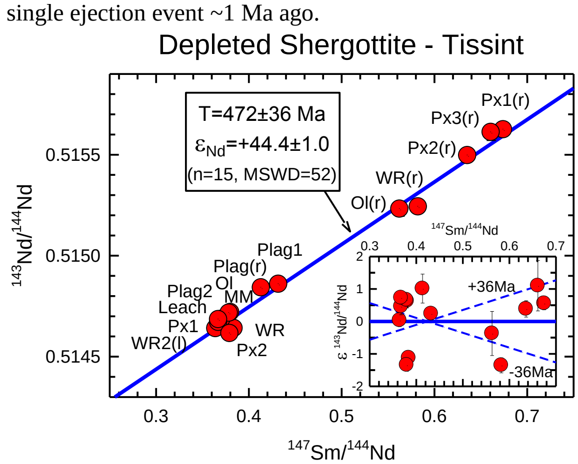

Figure 1. Sm-Nd isochron of Tissint.

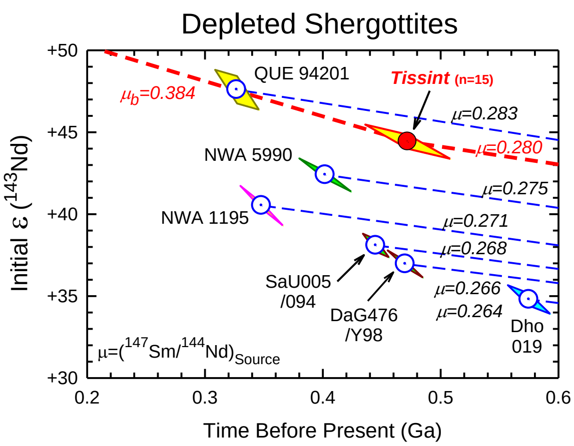

Figure 2. T(age) vs. ε_{Nd} of Depleted Shergottites.

Rb-Sr isotopic results: The $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ data for the same 15 Tissint samples (red circles) are shown in Fig 3. Unlike the Sm-Nd isotopic system in Fig 1, the Rb-Sr isotopic data are highly disturbed. Heavy shock metamorphism [2] seems to play an important role in the disequilibrium of the Rb-Sr isotopic system. However, such effects were less pronounced in six acid washed mineral samples and two unwashed plagioclase samples (red solid circles) which are collinear. Perhaps, the acid treatment eliminated most impact-induced melt pockets commonly located near the mineral contacts. These eight samples yield an age of 495±35Ma for $\lambda(^{87}Rb)$ =0.01402 Ga^{-1}, which is within error limits of the less disturbed Sm-Nd isochron shown in Fig. 1. The corresponding initial $^{87}Sr/^{86}Sr$ is 0.700767±29, the lowest value thus far found for a depleted shergottite, and was unaffected by shock metamorphism. The single-stage source $^{87}Rb/^{86}Sr$ is ~0.030. Five or six distinct Sr isotopic sources of low $^{87}Rb/^{86}Sr$ ratios (0.03-0.06) are identified for the seven depleted shergottites studied so far.

Petrogenetic implications: Petrogenetic models for depleted shergottites (DS) are demonstrated in a T(age) – initial ε_{Nd} plot in Fig. 4. Using a simple two-stage model, the mantle sources of these shergottites are implied to have super-chondritic $^{147}Sm/^{144}Nd$ of ~0.264-0.283 (green dotted line for Tissint in Fig 4; thin blue and red dotted lines in Fig 2). These high values suggest these shergottites were derived from strongly LREE-depleted mantle sources. To produce even more severely LREE-depleted melts with $^{147}Sm/^{144}Nd$ ~0.38-0.54 as found in the depleted shergottites (DS) by partial melting event(s) at 327-575 Ma ago is not straightforward. It would require multiple episodes of remelting of LREE-poor sources at 327 Ma, as suggested for the genesis of depleted shergottite QUE 94201 [16].

Alternatively, these depleted shergottites could have been produced by multi-stage processes, as also shown in Fig. 4. This model starts with the formation of a DS source precursor at ~4.353 Ga, soon after Martian core formation and mantle differentiation, and while the short-lived nuclides ^{146}Sm (most) and ^{182}Hf (some) were still alive [17-20]. This source precursor could have been a garnet-bearing peridotitic cumulate that crystallized during the early Martian mantle differentiation. The model cumulate source had nakhlite-like $^{147}Sm/^{144}Nd$ = ~0.233 (thick blue dotted line), but un-nakhlite-like low $^{87}Rb/^{86}Sr$ =~0.04. This source evolved until ~0.9-1.9 Ga (small blue circles and the red circle for Tissint), when partial melting produced LREE-enriched (nakhlite-like) melts and their corresponding highly LREE-depleted residues (blue thin dotted lines and red thin line for Tissint) in the time interval ~0.9-1.9 Ga ago. These residues would become the direct DS sources, from which DS finally were produced by large degree melting 327-575 Ma ago (open and solid red diamonds). This multi-stage model also can explain the nakhlite-like positive ^{142}Nd anomalies (~+0.6 ε) of DS [e.g. 17, 21, 3]. The Sm and Nd abundances of DS Yamato 980459 were reproduced by this model in [12].

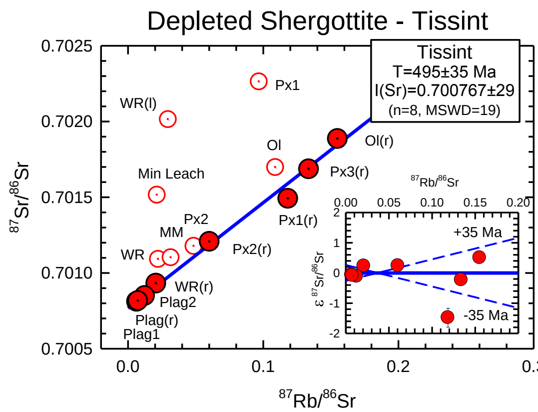

Figure 3. Rb-Sr isochron of Tissint.

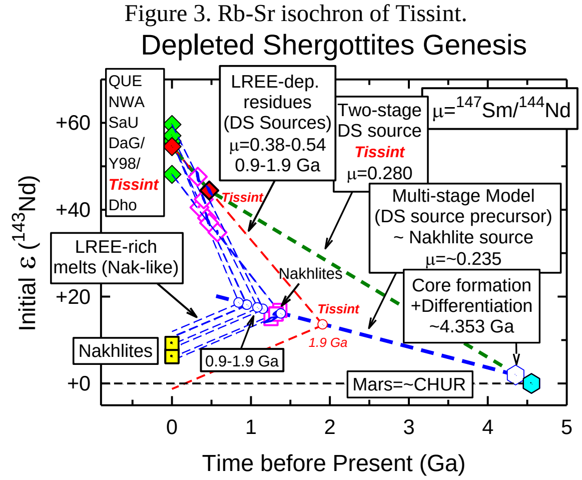

Figure 4. ε_{Nd} vs. T(age) of Dep. Sherg. & Nakhlites.

References: [1] Aoudjehane H.C. *et al* (2012) *Science*, **338**, 785-788. [2] Baziotis I.P. *et al* (2013) *Nat. Commun.* 4:1404 doi: 10.1038/ncomms2414. [3] Brennecka G.A. *et al* (2013) *LPSC 44*, CD-ROM #1786. [4] Grosshans T.E. *et al* (2013) *LPSC 44*, CD-ROM #2872. [5] Borg L. *et al* (2001) *LPSC 32*, CD-ROM #1144. [6] Nishizumi K. *et al* (2012) *MPS 75*, 5349.pdf. [7] Huber L. *et al* (2013) *LPSC 44*, CD-ROM #1534. [8] Shukolyukov Y.A. *et al* (2000) *MPS 63*, 5084.pdf. [9] Park J. *et al* (2013) *MPS 76*, 5320.pdf. [10] Ludwig K. (2003) Isoplot software package. [11] Borg L. *et al* (2003) *GCA* **67**, 3519-3536. [12] Shih C.-Y. *et al*. (2005) *Ant. Met. Res.* **18**, 46-65. [13] Shih C.-Y. *et al.* (2007) *LPS **XXXVIII***, CD-ROM #1745. [14] Bouvier A. *et al* (2013) *LPSC 44*, CD-ROM #2421. [15] Nyquist L.E. *et al* (2009) *GCA* **73**, 4288-4309. [16] Borg L. *et al.* (1997) *GCA* **61**, 4915-4931. [17] Harper C.L. Jr. *et al.* (1995) *Science* **267**, 213-217. [18] Jagoutz E. *et al*. (2000) *MPS.* **35**, A83-84. [19] Lee D.C and Halliday A.N. (1997) *Nature* **388**, 854-857. [20] Foley C.N. *et al* (2005) *GCA* **69**, 4557-4571. [21]Caro G. *et al* (2008) *Nature* **452**, 336-339.