RADIONUCLIDES IN THE TISSINT METEORITE: IMPLICATIONS FOR ITS MARTIAN ORIGIN. P. P. Povinec[1], C. Koeberl[2,3], A. J. T. Jull[4,5], I. Sýkora[1], L. Ferrière[2] and A. Kováčik[1,6], [1]Dept. of Nuclear Physics and Biophysics, Comenius University, 84248 Bratislava, Slovakia (pavel.povinec@uniba.sk), [2]Natural History Museum, 1010 Vienna, Austria (christian.koeberl@univie.ac.at; ludovic.ferriere@univie.ac.at), [3]Dept. of Lithospheric Research, University of Vienna, 1090 Vienna, Austria, [4]Dept. of Geosciences, University of Arizona, Tucson, AZ 85721, USA, [5]ICER, Institute for Nuclear Research, Hungarian Academy of Sciences, 4026 Debrecen, Hungary, [6]MicroStep-MIS, 84104 Bratislava, Slovakia.

Introduction: Martian meteorites were ejected from the planet Mars by the impact of asteroids or comets before they finally landed on the Earth. They carry information on the composition and characteristics of Mars surface and subsurface depending of the crystallization and ejection depth, and therefore they are unique samples, as there are currently no other possibilities to investigate the subsurface of Mars. These meteorites have elemental and isotopic compositions similar to rocks analyzed by spacecrafts and also contain trapped atmospheric gases similar to the Martian atmosphere. Of more than 60,000 meteorites currently known, only 224 are of Martian origin (some of them are paired); they are divided by chemical and mineralogical properties into three main groups, with more than three-quarters being shergottites [1–7].

Tissint, a recent fall on July 18, 2011 in Morocco, is an olivine-phyric basalt, consisting mainly of olivine phenocrysts in a fine-grained pyroxene-maskelynite matrix, with minor chromite, ilmenite, pyrrhotite, and phosphates [1, 5]. Tissint is heavily shocked, showing shock-melt veins and pockets, the result of multiple shock events [1, 2, 5, 6].

Here we report on our investigation of primordial (^{40}K, ^{232}Th, and ^{238}U), and cosmogenic radionuclides with half-lives from about one year to about 0.7 Myr, which were analyzed by non-destructive gamma-ray spectrometry (^{54}Mn, ^{22}Na, ^{60}Co, and ^{26}Al) and by Accelerator Mass Spectrometry (AMS) (^{14}C).

Samples and Methods: Two fragments of the Tissint meteorite, both from the NHM Vienna collection, with masses of 37.7 and 908.7 g (samples N9412 and N9388, respectively) were used for the present work. The bulk main elemental composition (i.e., Fe, Mg, Ca, Al, and Mn) of Tissint is similar to other depleted olivine-phyric shergottites [1]. When compared to H type ordinary chondrites, the abundance of these elements are lower by a factor of about two, however, for Co, its concentration is 10x lower [8].

Gamma-spectrometry analyses of the two fragments of the Tissint meteorite were carried out in the Low-Level Gamma-Spectrometry Laboratory of the Department of Nuclear Physics and Biophysics of the Comenius University in Bratislava (Slovakia). A low-background HPGe detector with relative detection efficiency of 70% operated in the coincidence-anticoincidence mode in a large low background lead/polyethylene/copper shield with dimensions of $1.5 \times 1.5 \times 2$ m was used [9]. Detailed descriptions of the calibration and corrections are given by [10]. The quoted uncertainties of the results are mainly due to counting statistics; the measuring time was 10 days for the large sample and 14 days for the smaller one.

For the ^{14}C analyses, a 188 mg sample, from the NHM-Vienna_Tis10 fragment, was selected for AMS measurements. The cosmogenic ^{14}C was extracted in a RF induction furnace in a flow of oxygen, and passing the evolved gases over a CuO furnace to ensure conversion to CO_2. This gas was collected and measured volumetrically. The CO_2 was then converted to graphite and analyzed on a 3 MV AMS machine at the University of Arizona (USA). The full procedure for ^{14}C measurements is given in [11, 12].

Results: The results are presented in Table 1. Several gamma-lines were identified in the gamma-ray spectra representing ^{22}Na, ^{26}Al, and ^{54}Mn. The activities of ^{22}Na, ^{26}Al, and ^{54}Mn measured in both fragments were similar within 1σ statistical uncertainties. The average ^{22}Na and ^{26}Al activities in the small and large samples are 65.4±4.6 and 36.9±3.1 dpm/kg, respectively. The ^{22}Na/^{26}Al activity ratio for the large sample (i.e., measured with better precision) is 1.89±0.05, which is higher than typical values for H chondrites (i.e., 1.5), averaged for several 11-yr solar cycles between 1970 and 2000 [13]. The higher ^{22}Na/^{26}Al activity ratio observed for Tissint can be explained by an unsaturated production of ^{26}Al, which was caused by its short cosmic-ray exposure age, as discussed in the next paragraphs. Unfortunately, short-lived radionuclides with half-lives shorter than one year had already decayed when we conducted our measurements, and their activities were below detection limits. The ^{60}Co radionuclide (possible indicator of the burial depth of the specimen) was not identified, only detection limits could be reported, <0.2 and <1.9 dpm/kg (at 90 % confidence level), for the large and the small specimens, respectively. The ^{14}C measurements of 42.6±0.4 dpm/kg are in agreement with expectations. The average activities of the primordial radionuclides in the Tissint meteorite are 280±50 dpm/kg for ^{40}K, 2.4±0.6 dpm/kg for ^{238}U, and 1.8±0.6

dpm/kg for ^{232}Th, comparable to the average concentrations given in [8].

Table 1. Cosmogenic radionuclides in Tissint samples.

Mass	^{22}Na	^{26}Al	^{54}Mn	^{60}Co$^{\#}$	^{14}C
(g)			(dpm/kg)		
37.7	62.3±4.0	37.7±2.8	52.4±7.6	<1.9	
908.7	68.5±2.3	36.2±1.3	55.7±2.5	<0.2	42.6±0.4*

The measured activities were decay corrected to July 18, 2011. *Sample weight was 188 mg.

Pre-atmospheric radius (PAR) of the Tissint meteorite: The ^{60}Co is mainly produced by the capture of thermal neutrons on ^{59}Co nuclei, and is usually used as an indicator for the depth of a meteorite within the meteoroid body, as well as for the estimation of the radius of the meteoroid body (see e.g., [14,15]). The absence of ^{60}Co in the analyzed samples indicate either a small concentration of the target isotope ^{59}Co in the meteorite, and/or a small radius of its meteoroid body. The cobalt concentration was measured to be 58 ppm in the Tissint meteorite [1], which is lower by a factor of 10 when compared to H chondrites [8]. Using the measured ^{60}Co limit (<0.2 dpm/kg) for the large sample, and Monte Carlo modeling results [16] (after appropriate corrections for the chemical composition), we can estimate the pre-atmospheric radius of the Tissint meteorite to be <20 cm.

The other radionuclides identified in the Tissint samples, ^{14}C, ^{22}Na, ^{26}Al, and ^{54}Mn, were produced by interaction of secondary cosmic-ray protons and neutrons mainly on the O, S, Al, Si, and Fe nuclei. The production rates of ^{22}Na and ^{54}Mn due to their short half-lives also depend on variations of cosmic-ray fluxes during the 11-yr solar cycle. On the other hand, the production of ^{26}Al is averaged during about 1.5 Myr due to its long half-life (0.717 Myr). Although its production rate does not change significantly at larger depths, in small meteorites with radius <20 cm, a steep rise of the production rate with depth is predicted [16], which can also be used for the estimation of their pre-atmospheric size. Following a similar approach as for ^{60}Co, the Tissint radius can be estimated to be 20±3 cm. The mass of the meteoroid would then be of 100±15 kg (for an average bulk density of 3 g/cm^3). The measured ^{14}C activity of 42.6±0.4 dpm/kg, scaled to the H-chondrite data [17], suggests a radius of about 15 to 20 cm, in line with the ^{60}Co and ^{26}Al results, and similar to the 15 to 25 cm derived from ^{10}Be concentration measurements [7]. The estimated size and mass are typical for other depleted permafic olivine-phyric shergottites as well [18].

Cosmic-ray exposure age (CRE) of the Tissint meteorite: The $^{\mathbf{26}}$Al method described by [3] was used for the estimation of the CRE age of the Tissint meteorite. Although we have only ^{26}Al measurements in two samples with unknown depths in the meteoroid, we can expect at least for the large sample (i.e., because of its large size and the small radius of the meteoroid) its position to have been close to the meteoroid surface. The calculated CRE exposure age of 0.9±0.3 Myr agrees well with previous works, 0.7±0.3 Myr based on ^{3}He, ^{21}Ne, and ^{38}Ar [1] and 1.10±0.15 Myr based on ^{10}Be [7]. These estimates are consistent with CRE ages of similar Martian meteorites (e.g., EETA79001, DaG 476, DaG 735, NWA 1195, NWA 2046, NWA 2626, NWA 4925, NWA 5789, SaU 005, and Yamato 980459), which have an average CRE age of 1.05±0.10 Myr [7], suggesting that the group of depleted permafic olivine-phyric shergottites was likely ejected from Mars at the same time, around 1.05±0.10 Myr.

Acknowledgement: The Bratislava group acknowledges the support provided by the Slovak Grant Agency VEGA (1/0891/17), as well as by the EU Research and Development Operational Program funded by the ERDF (26240120012, 26240120026). AJTJ was partly supported by the EU and Hungary through the ERDF project GINOP-2.3.2.-15-2016-00009 'ICER'

References: [1] Chennaoui Aoudjehane H. et al. (2012) *Science 338*, 785–788. [2] Baziotis I.P. et al. (2013) *Nature Communications 4*, 1404. [3] Herzog G.F. (2005) Cosmic-ray exposure ages of meteorites. In Davis A.M. (ed.) *Meteorites, Planets, and Comets.* Elsevier, p 347–380. [4] Eugster O. et al. (2006) Irradiation records, cosmic ray exposure ages, and transfer time of meteorites. In Lauretta D. and McSween H.Y.Jr. (eds.) *Meteorites and the Early Solar System II*, University of Arizona Press, pp. 829–851. [5] Irving A.J. et al. (2012) LPS *XXXXIII*, 2510. [6] Hallis L.J. et al. (2017) *Geochim. Cosmochim. Acta, 200*, 280–294. [7] Nishiizumi K. et al. (2012) *Meteoritics & Planet. Sci.* #5349. [8] Wasson J.T. and Kallemeyn G.W. (1988) *Phil. Trans. Royal Soc., A325*, 535–544. [9] Povinec P.P. et al. (2009) *J. Radioanal. Nucl. Chem., 282*, 805–808. [10] Kováčik A. et al. (2013) *J. Radioanal. Nucl. Chem., 298*, 665–672. [11] Jull A.J.T. et al. (1993) *Meteoritics, 28*, 188–195. [12] Jull A.J.T. et al. (2010). *Meteoritics & Planet. Sci., 45*, 1271–1283. [13] Bhandari N. et al. (2002) *Meteoritics & Planet. Sci.., 37*, 549-564. [14] Povinec P.P. et al. (2015) *Meteoritics & Planet. Sci., 50*, 880–892. [15] Povinec P.P. et al. (2015) *Meteoritics & Planet. Sci., 50*, 273–286. [16] Leya I. and Masarik J. (2009) *Meteoritics & Planet Sci., 44*, 1061–1086. [17] Wieler R. et al. (1996) *Meteoritics & Planet. Sci., 31*, 265-272. [18] Britt D.T. et al. (2012) *Meteoritics & Planet. Sci., 47*, #5350.