Launch conditions for Martian Meteorites: Plagioclase as a shock pressure barometer. J. Fritz, A. Greshake, and D. Stöffler, Institut für Mineralogie, Museum für Naturkunde, Humboldt Universität zu Berlin, Invalidenstraße 43, 10115 Berlin, e-mail: joerg.fritz.1@rz.hu-berlin.de.

Introduction: It is generally accepted that the 23 unpaired SNCO meteorites were ejected by hypervelocity impacts from the Martian surface [1]. The ejection ages of the Martian meteorites which range from 0.73 and 20 Ma, imply that at least five impact events are required to transfer this group of meteorites to Earth [2]. From the time-calibrated cratering statistics [3] it must be concluded that the large number of ejection events in this short time interval require rather small craters (<3 km) for the ejection of the Martian meteorites. New computer simulations of hypervelocity impacts on Mars also indicate that the ejection of Martian meteorites from small craters is possible [4, 5]. To understand the process of mass transfer from Mars to Earth it is essential to know the final equilibration shock pressure of all Martian meteorites which defines the p/T-launch window. In this work we present data for the final equilibration shock pressure of 16 Martian meteorites.

Method: The shock-induced transformation of plagioclase to crystals of lower density, to diaplectic and to normal glass was experimentally calibrated by shock recovery experiments [6 and references therein]. It was shown that the refractive index of shocked plagioclase is a function of the shock pressure and An-content and can thus be used to determine the final equilibration pressure in natural samples. In this study we measured the refractive index of single plagioclase or maskelynite grains in 16 Martian meteorites applying the λ-T method [7]. The accuracy of the refractive index determination is about ± 0.0005. The An-content of the polished grains was determined using a JEOL-JXA-8800L electron microprobe with a defocussed electron beam of 5 µm at 15 kV accelerating voltage and a beam current of 15 nA. The results of the refractive index measurements are plotted versus the An-content of the measured plagioclase grains (Fig. 1 a, b). From the calibration curves of Figure 1 a and b shock pressures are derived for each measured area of the individual plagioclase grains. The average values and the standard deviation for each meteorite were calculated (Table 1).

Results: For each meteorite we observe some variation in the refractive index values and An-contents. This variation is particularly pronounced in Shergotty, Dhofar 019, EETA79001, ALH84001, and SaU 005, obviously reflecting a certain variation of plagioclase composition and shock pressure within the meteorite. For plagioclase in the two nakhlites Lafayette and Y000593 no reduction of birefringence or index of refraction could be detected. However, other minerals in these meteorites display distinct shock metamorphic features, e.g. polysynthetic twin lamella in pyroxene indicating that the meteorites were shocked between 5 and 14 GPa.

All plagioclases in Nakhla, Governador Valadarez, and Chassigny plot below n_y indicating a reduction of the refractive index for each of these meteorites.

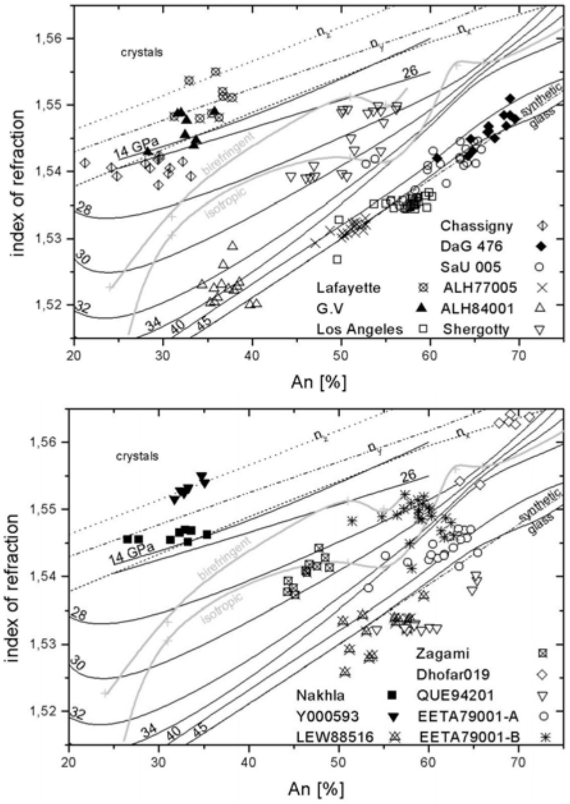

Fig. 1a and b: Refractive index versus An-content of plagioclase of Martian meteorites, data for n_x, n_y, n_z, and glass from [8], isobars in GPa and lines for birefringent and isotropic fields from [6].

The partly birefringent character of plagioclase in Zagami, Shergotty, Dhofar 019, and EETA79001-B, which is visible under the optical microscope, was confirmed by the refractive index measurements. Several data points for these meteorites plot in the field between the boundary curves for the isotropic and birefringent state. For EETA79001 plagioclase from a more coarse-grained (probably lithology B) and from a fine-grained sample (probably lithology A) were analyzed. Both lithologies display different pressure signatures with the coarse-grained sample being shocked to lower pressures.

ALH84001 shows a wide range of shock metamorphism, possibly due its lithological heterogeneity (brecciation zones).

Maskelynite in the highly shocked meteorites DaG 476, SaU 005, and ALH77005 have a refractive index close to the one of synthetic glass.

Tab. 1. Final equilibrium shock pressure with standard deviation in GPa of this work compared to literature data (av. = average, s.d. = standard deviation).

	Pressure av. ± s.d. [GPa]	
Meteorite	**This Work**	**Literature**
Shergotty	28.4 ± 1.7	29 ± 1 [6]
Zagami	29.2 ± 0.6	31 ± 2 [6] 27 [10] 29.3 [9]
Dhofar 019	30 ± 7.9	
Los Angeles	44.4 ± 1.9	
QUE94201	~ 45	
EETA79001 – A	38.1 ± 2.8	34 ± 1 [10]
EETA79001 – B	30.5 ± 3.9	34 ± 1 [10]
DaG 476	42.9 ± 2.0	
SaU 005	42.9 ± 3.7	
LEW88516	44.3 ± 1.9	
ALH77005	44.2 ± 1.8	43 ± 2 [6] 45 [10]
Lafayette *	5 - 14	
Y000593 *	5 - 14	
Nakhla **	14 - 20	
Governador V. **	14 - 20	
Chassigny **	26.6 ± 0.5	~ 35 [11]
ALH84001	35.7 ± 4.5	

*Lafayette and Y000593 are shocked below resolution of the applied method (< 14 GPa).

** minimum shock pressure is due to unknown orientation of the birefringent crystals.

The indices of refraction for maskelynite in Los Angeles, LEW88516, and QUE94201 surprisingly plot below the line of synthetic glass. The low index of refraction can be explained by a shock induced loss of Na and K.

The shock pressure data derived from plagioclase are also consistent with all other observable shock metamorphic features in the analyzed Martian meteorites.

Conclusions: The high precision shock barometry obtained for 70 % of the known Martian meteorites represents a substantial improvement in quantity and quality compared to with previously reported shock barometry [6, 9,10]. If one takes into account that 6 of the remaining 7 meteorites for which high precision shock barometry is not yet available, contain definitely maskelynite [12], the equilibration shock pressure of these 6 meteorites must be in the range of ca. 25 to about 40 GPa. This means that for 95 % of the known Martian meteorites the equilibration shock pressure ranges between 5 and 45 GPa. In other words, there are no unshocked Martian meteorites. The observed range of shock metamorphism of Martian meteorites is in good agreement with the boundary conditions (9–45 GPa) obtained from three-dimensional numerical simulations of oblique impacts on Mars [4].

Moreover, accepting 5-8 ejection events for all Martian meteorites [1,2, 4] we must conclude that from single impact events meteorites of different shock intensity were ejected and delivered to Earth.

In conclusion, proposed models invoking mechanism to transfer "unshocked" rocks from Mars to Earth are incorrect and the total mass of Martian rocks transferred to Earth supposed to be much smaller than previously assumed [13]. The potential delivery of bacterial life from Mars to Earth is restricted correspondingly because of the high post-shock temperature increase exceeding 250 K [6] for some 80 % of the known Martian meteorites.

Acknowledgements: We thank H. Schneider, H. Schick, J. Berlin, and H. Knöfler for their excellent technical support. The authors gratefully acknowledge the generous supply of the samples by the Natural History Museum, London the Meteorite Working Group, Museum National d'Historie Naturelle, Paris, the Max-Planck-Institut für Chemie, Mainz, Institute of Geophysics and Planetary Physics, Los Angeles, National Institute of Polar Research, and the finder of DaG 476.

References: [1] Nyquist L. et al (2001) *Space Sci Rev.* **96**, 105-164. [2] Eugster et al. (2002) *MAPS* **37**, 1345 – 1360. [3] Neukum G. (1976) *Science* **194**, 1381 – 1387. [4] Artemieva N. & Ivanov B. A. (2002) *LPSC* **XXXIII**, #1113. [5] Head J. N. et al. (2002) *Science* **298**, 1752 – 1756. [6] Stöffler D. et al. (1986) *GCA* **50**, 889 - 903. [7] Fritz J. et al. (2002) *LPSC* **XXXIII**, #1504. [8] Tröger W. E. (1982) Optische Bestimmung der gesteinsbildenden Minerale, Schweizerbart, Stuttgart. [9] Langenhorst F. et al. (1991) *LPSC* **XXII**, 779 - 780. [10] Lambert P. (1985) *Meteoritics* **20**, 690 - 691. [11] Langenhorst F., & Greshake A. (1999) *MAPS* **34**, 43 - 48. [12] Meyer C. *Mars Meteorite Compendium*, NASA, Houston. [13] Mileikowsky et al. (2000) *Icarus* **145**, 391 – 427.