COMPLEX THERMAL HISTORY OF NAKHLA AND Y000593. A. Szymanski[1], F.E. Brenker[1], A. El Goresy[2] and H. Palme[1], [1]Universität zu Köln, Inistitut für Mineralogie und Geochemie, Zülpicherstr. 49b, 50674 Köln, Germany, a.szym@rz.uni-leipzig.de, brenker@min.uni-koeln.de, palme@min.uni-koeln.de, [2]Max-Planck Institut für Chemie, Joh.-J.-Becher-Weg 27, 55128 Mainz, Germany, goresy@mpch-mainz.mpg.de

Introduction: In order to unravel the thermal history of the Martian meteorites Nakhla and Y000593 we applied several geo-thermometers including single and two pyroxene thermometry, the Fe, Ti- thermometer / oxybarometer and TEM microstructures.

Application of the Fe,Ti-thermometer/oxybarometer: The presence of Fe,Ti-oxide phases enable the application of the Fe,Ti-thermometer /oxybarometer [1,2] to define fO_2 and closure temperature of the oxide pair. The method is based on the Fe and Ti exchange between coexisting rhombohedral oxide (ilmenite solid solution) and spinel (titanomagnetite solid solution) pairs, which determines the closure temperature. The activities of magnetite in spinel and of hematite in ilmenite are used to constrain the fO_2 at the respective temperature. The most recent versions of this model include Ghiorso/Sack [2], which was developed to account for minor-element substitution in the oxides, and the Ca-QUILF model of Andersen [1], which considers equilibria between titanoferous magnetite, ilmenite, augite, pigeonite, orthopyroxene, olivine and quartz in the system FeO-CaO-MgO-SiO_2-TiO_2. Typically, fO_2 determinations are made using the Fe^{3+}/Fe^{2+} ratios of these oxides at closure temperatures. The procedure requires oxide intergrowths large enough to allow clean electron microprobe analyses. The temperature – $\log fO_2$ data for the Nakhlites Nakhla are: Ghiorso/Sack: $\log fO_2 = -14.21$ and T = 824 °C, Δ FMQ = -0.20 and Ca-QUILF: $\log fO_2 = -14.49$ and T = 795 °C, Δ FMQ = 0.14 and for the new antarctic meteorite Y000593: Ghiorso/Sack: $\log fO_2 = -15.22$ and T = 811 °C, Δ FMQ = -0.94; Ca-QUILF: $\log fO_2 = -15.19$ and T = 790 °C, Δ FMQ = -0.46. The results indicate an fO_2 near the FMQ buffer relevant for most of the terrestrial rocks in the lower earth crust. The absolute error of the oxygen fugacity estimates is ± 0.5 log units. The results indicate slight differences in fO_2 between Nakhla and Y000593. The new Nakhlite may have crystallized under more reducing conditions compared with the Nakhla meteorite. Furthermore, there are large differences in the fO_2, by 3 log units or more between Nakhla, Y000593 on the one hand, and other SNC meteorites on the other [3,4]. These differences may reflect variations in the degree of oxidation very early in the history of planet Mars.

Clinopyroxene thermometry: Further details of the thermal history of nakhlites can be obtained by applying single and two pyroxene thermometers. However, in order to avoid problems with equilibration of clinopyroxene-olivine pairs we restrict our discussion to the estimation of the minimum temperature required to form a clinopyroxene with a certain composition based on the phase diagram of Linsdley [5].

In both nakhlites the clinopyroxenes consists of large homogenous Fe-poor cores (Nakhla: $En_{44-46}Wo_{34-35}Fs_{20-22}$; Y000593: $En_{44-46}Wo_{34-35}Fs_{20-22}$) with small Fe-rich zones at the rim of the crystals in contact with Fe-rich olivine or melt (Nakhla: $En_{22-35}Wo_{30-34}Fs_{30-47}$; Y000593: $En_{14-35}Wo_{30-34}Fs_{30-55}$). We estimate for the core composition minimum temperatures of 1150°C required to form a clinopyroxene of the respective composition. The minimum temperature required for the Fe-rich rims range from 1050 to 1150°C for Nakhla and 1000-1150°C for Y000593. For clinopyroxenes in the mesostasis the required minimum temperatures are about 850 to 1150°C for both nakhlites.

TEM-Microstructures: The type and size of pigeonite exsolution in augite or vice versa can be used to determine the temperature-time evolution of each clinopyroxene [6]. The size and type of exsolution depend on temperature, cooling rate and composition. Weinbruch and Müller [7] found that with increasing Fe-content the coarsening of exsolution lamellae on (001) is slower.

Our TEM study revealed that the Fe-poor cores of the clinopyroxenes are free of lamellar exsolution features. Only a slight modulation of the structure can be seen. The absence of exsolution in the clionopyroxene cores requires fast cooling rates, more than several degrees per hour [6].

In contrast, the FeO-rich rims and the clinopyroxenes in the mesostasis show extensive exsolutions parallel (001) and (100) which requires cooling rates lower than 0.005°/hr. With increasing Fe-content the width of the exsolution lamellae increase which is opposite to the trend expected from experimental data [7]. Similar exsolution features were also decribed by [8] for Fe-rich rims in pyroxenes of Nakhla, Governador Valadares and Lafayette using FEG-SEM. It should be noted as well that the complex microstructure (Fig. 1) found in the clinopyroxenes within the mesostasis is identical to most observations made by Müller [9] on clinopyroxenes in Shergotty, which includes size and orientation of the exsolution lamellae as well as twinning and stacking faults parallel (001).

Only features related to the higher schock stage of Shergotty are absent. The cooling rate determined from shergotty pyroxenes is in the order of 0.002°/hr [9].

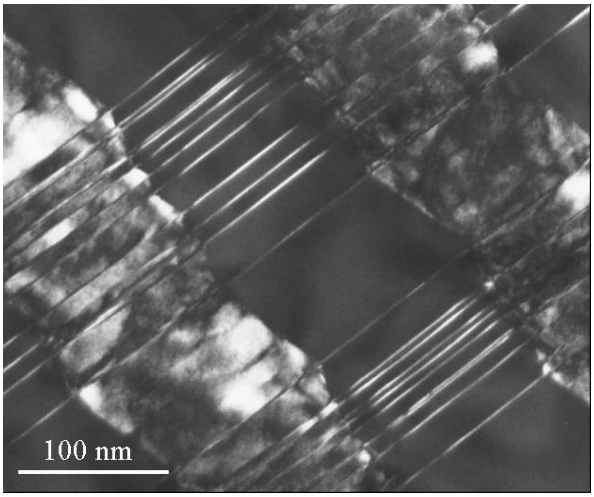

Figure 1. TEM dark field electron micrograph of the complex microstructure of Fe-rich clinopyroxene from the mesostasis of Nakhla using a reflection of pigeonite. Pigeonite exsolution lamellae parallel (001) and mechanical twins and stacking faults on (100). Pigeonite lamellae and stacking faults are in contrast under these dark field conditions.

Discussion: Based on our calculations and observed microstructures we conclude that after formation and extensive thermal equilibration of the clinopyroxene crystals at temperatures above 1150°C, these crystals must have been rapidly transported to a location close to the surface of planet Mars, where they cooled rapidly inside a small dyke or lava flow. The large pyroxene crystals had to be cooled down with a cooling rate faster than several degrees per hour in order to prevent exsolution of Ca-poor pyroxene.

Impregnation of a highly oxidizing, high temperature melt reheated the pyroxenes, but affected only the outer rims of the clinopyroxenes. Any reheating of the clinopyroxene cores to higher temperatures would have led to the exsolution of low Ca-pyroxene. The cooling rate of the melt was in the order of 0.002°/hr. The proposed two-stage model is in contrast to previous models dealing with a more or less continuous cooling process with subsolidus annealing with an evolving melt [8,10] but in good agreement with the suggestion that nakhlites formed in a lava flow located near the surface of planet Mars [11].

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