A 3-D STUDY OF INCLUSIONS IN EXTRATERRESTRIAL CHROMITE USING SYNCHROTRON RADIATION X-RAY TOMOGRAPHIC MICROSCOPY C. Alwmark[1,2], B. Schmitz[1], S. Holm[1], F. Marone[3], M. Stampanoni[3,4], [1]Dept. of Geology, University of Lund, Sölvegatan 12, SE-22362 Lund, Sweden, carl.alwmark@erdw.ethz.ch, [2] Inst. for Geochemistry and Petrology, ETH Zürich, Clausiusstrasse 25, CH-8092 Zürich, Switzerland, [3]Swiss Light Source, Paul Scherrer Inst., 5232 Villigen, Switzerland, [4]Inst. for Biomedical Engineering, University and ETH Zürich, CH-8092 Zürich

Introduction: Here we describe a method for imaging in 3-D the interiors of meteoritic chromite grains and their inclusions using synchrotron radiation X-ray tomographic microscopy (SRXTM). In ordinary chondrites, chromite is the only common mineral that survives long-term exposure on Earth. However, a recent study [1] showed that coarse chromite grains from ordinary equilibrated chondrites contain small inclusions of the matrix minerals of the meteorite and that information about the silicate matrix of the original meteorite can be derived from these inclusions. Thus, the inclusions are an important tool in classification (H, L, LL) of fossil extraterrestrial chromite used for characterizing the past influx of material to Earth, but have previously been difficult to locate using a method of layer-by-layer polishing of the host chromite grain.

The main aim of this study is to, with the help of SRXTM, develop a non-destructive technique in which large amounts of chromite grains can be scanned and inclusions located in a relatively short time. Previous studies using SRXTM on extraterrestrial material include [e.g. 2-4]. Using SXRTM will also allow, for the first time, quantitative and morphological studies of both host chromite grain and inclusions in three dimensions. By analyzing inclusions in chromite from recent chondrites of different groups, petrographic types and shock stages, we can determine variations in size and shape distribution, as well as in the abundance of inclusions between these groups. Information that then can be used in the classification of fossil meteoritic material.

Material and Methods: Chromite grains from eight equilibrated (type 4-6) ordinary chondrites of the different groups (H, L, LL), and with varying degree of shock metamorphism were searched for inclusions. The chromite grains were vertically stacked in low x-ray scattering capillary glass tubes, with each chromite grain separated by a small glass bead, thus enabling each grain to be scanned separately. A total of 385 chromite grains distributed over 20 capillaries were prepared. The grains were then analyzed using SRXTM at the TOMCAT beamline of the Swiss Light Source at the Paul Scherrer Institute, Switzerland [5]. The beam energy was set to 17.5 keV and the X-ray radiation was converted into visible light by a 20 µm thick Ce-doped LAG scintillator screen. Projection images were digitized by a high-resolution CCD-camera. The optical magnification was set to 20x, resulting in isotropic voxels of 0.37 µm in the reconstructed datasets. 1501 projections were acquired for each scan with an exposure time of 300 ms for each projection. An automatic sample exchanger integrated at the TOMCAT beamline [6] enabled the unattended measurement of the 385 chromite grains over the course of 26 hours. The tomographic reconstructions were performed using a highly optimized routine based on the Fourier transform method and a gridding procedure [7]. The reconstructed datasets were 3D rendered using commercial software (Voxler) where the number of inclusions was counted and the sizes of both the host chromite grains and the inclusions were measured.

In order to verify the existence of the inclusions and to determine their mineralogy, six grains, containing inclusions according to the tomographic data, from each sample were polished and studied using a scanning electron microscope (SEM; Hitachi S-3400N) and an energy dispersive spectrometer (EDS; Inca X-sight from Oxford instruments).

Results and Discussion: Analysis of the data, in the form of tomograms, reveals that inclusions as well as cracks are readily distinguished down to a resolution of <1 µm (Figs. 1a and 1b) and that inclusions are equally common in all samples. Almost 2/3 (64%) of all grains contained one or more inclusions. The number of inclusions within each chromite grain varies from solitary inclusions to over 300. The average

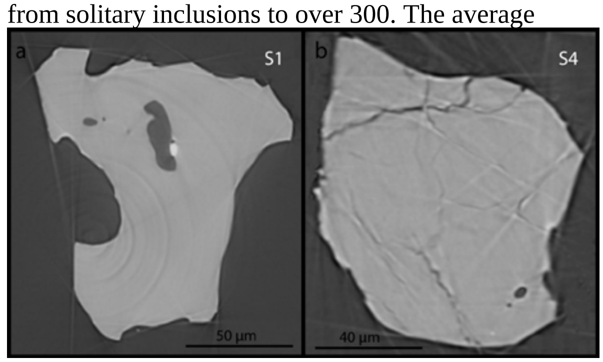

Fig. 1. Virtual slices through microtomograms of chromite grains with inclusions and different degrees of fracturing. Also shown are the previously assigned shock stages (S1-S6) of the chondrites that the chromite grains derive from. a) Grain with polymineralic inclusion of silicate and metal/troilite extracted from H6 chondrite Kernouvé. Also note the absence of fractures. b) Relatively fractured grain with two small inclusions in the lower right corner, extracted from L5 chondrite Farmington.

number of inclusions in chromite grains from samples of petrographic type 4 is about twice as high (33 inclusions grain^{-1}) compared to types 5 and 6 (15 inclusions grain^{-1}, respectively).

The size of the inclusions range from <1 to 2.4×10^5 μm^3, though typically between 4 and 100 μm^3 and are anhedral to subhedral in shape. A comparison of the average size of the largest inclusion from each chromite grain shows that chromite grains from the samples of petrographic type 6 contain the largest inclusions, with an average size that is more than 20 times larger than that of grains from type 4 and 5 meteorites. Thus, provided that a sufficient amount of grains is analyzed, it is possible to obtain an estimation of petrographic type of fossil equilibrated ordinary chondritic meteorites, based on number and size distribution of inclusions in chromite grains. The increase in inclusion size with petrographic type is most likely the result of the general trend of coarsening of matrix minerals with increase in thermal metamorphism. The coarsening of matrix minerals is also the reason for the decrease in average number of inclusions per chromite grain with petrographic type, as the number of individual mineral grains is reduced with increase in matrix grain size.

Irregular fractures are common in varying degrees in the chromite grains of the samples. The amount of fractures correlate with the previously assigned shock stages for the different chondrite samples (S1-S6), with an increase in the amount of fractures with increasing shock stage (Figs. 1a and 1b). Thus, an estimate of the shock metamorphism a meteorite has been subdued to can be assessed based on the amounts of fractures within the chromite grains.

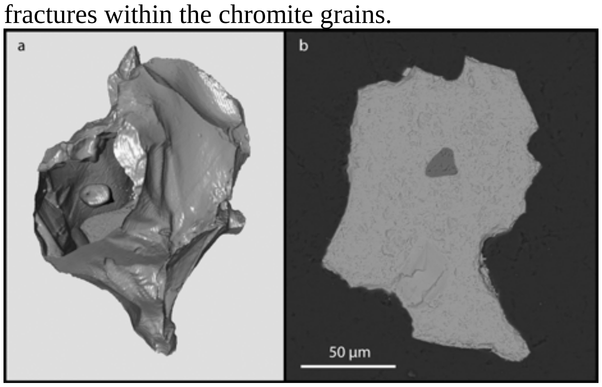

Fig. 2. a) 3-D rendered image of chromite grain extracted from H6 chondrite Kernouvé with inclusion of Ca-poor pyroxene. b) SEM backscatter image of the same chromite grain, now mounted in epoxy and polished down to display the inclusion.

Inclusions were identified and could be correlated to those observed in the respective microtomograms (Figs. 2a and 2b) in all of the chromite grains that were studied using SEM/EDS. The most common minerals of the inclusions analyzed are pyroxene, both Ca-poor and Ca-rich (diopside), olivine, and merillite, in that order. Furthermore, the Fa content of the olivine and the Fs content of the Ca-poor pyroxene analyzed are consistent with the defined ranges for inclusions in chromite for the different ordinary chondrite groups [1].

Conclusions: The method used in this study to identify and examine inclusions in chromite grains, by analyzing them using SRXTM, allows for large amounts of grains to be analyzed in a short time with high spatial and contrast resolution. Furthermore, the method is non-destructive and does not affect the properties of the material analyzed, i.e. grains of interest can be recollected and further studied using other methods.

The information acquired from the studied material led us to conclude:

- Inclusions are equally common in all samples, and almost 2/3 of all chromite grains contained inclusions.
- The size of the inclusions as well as the number of inclusions within the host grains vary with petrographic type; chromite from type 6 chondrites contain few and large inclusions; type 5 grains hold few and small inclusions and petrographic type 4 contain many and small inclusions.
- The amount of fractures in the host chromite increases with increase in shock stage of the chondrite.

Thus, based on chromite grains and inclusions therein, the petrographic type as well as shock stage can be assessed of the precursor meteorite. This together with the previous study showing that the group of the host meteorite can be determined based on the composition of the inclusions, and the high percentage of inclusion-bearing grains, regardless of group and type, show that inclusions are a crucial and valuable tool in reconstructions of the past meteorite flux to Earth.

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References: [1] Alwmark C. and Schmitz B. (2009) *GCA 73*, 1472–1486. [2] Ebel D. S. and Rivers M. L. (2007) *MAPS 42*, 1627–1646. [3] Ebel D. S. et al. (2008) *MAPS 43*, 1725–1740. [4] Friedrich J. M. et al. (2008) *EPSL 27*, 172–180. [5] Stampanoni M. et al. (2006) *Proc. of SPIE 6381*. [6] Mader K. et al. (2010) *J. Synchrotron Radiat.*, in press. [7] Marone F. et al. (2010) *Proc. of SPIE 7804*.