NAKHLITES AND NANOSIMS VIA MICRO-CT CHARACTERISATION. A. W. Needham\textsuperscript{1,2}, T. O. R. Tomkinson\textsuperscript{1}, C. Guillermier\textsuperscript{1}, R. L. Abel\textsuperscript{2}, I. A. Franchi\textsuperscript{1}, M. M. Grady\textsuperscript{1,2}, \textsuperscript{1}PSSRI, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK. (A.W.Needham@open.ac.uk). \textsuperscript{2}IARC, Department of Mineralogy, The Natural History Museum, London, SW7 5BD, UK.

**Introduction:** The nakhlite meteorites contain many mineral phases that precipitated from aqueous solutions and/or were produced by the aqueous alteration of primary igneous minerals. These minerals provide an important record of the history of water on the surface and subsurface of Mars. The isotopic composition of these minerals provides valuable information for reconstructing the physical and chemical environment during formation, as well as the likely geological setting in which fluids were present. In order to reconstruct fully the history of these samples it is essential to understand the multiple episodes of aqueous activity, the relationship between the various carbonate, clay and sulphate phases, and the intricate network of veins and fractures hosting the alteration mineral assemblages.

**Methods:** A novel 3D approach has been used for sample characterisation prior to sample preparation and destructive analyses. Using a Metris X-Tek HMX ST 225 System we scanned two small (~1.1g total) sections of Nakhla at a resolution of ~5µm per voxel, producing several thousand slices, subsequently reconstructed to provide 3D representations of the samples. Assigning CT (grey) values to voxels of different linear attenuation coefficients (i.e. density) permits different mineral phases, and fractures, to be identified.

Areas of interest identified in tomographic data can be exposed by standard cutting procedures, followed by SEM analyses. Samples for NanoSIMS analyses ideally have minimal topography. This can be achieved by either standard cutting/polishing, or by using the focused ion beam in the FIB-SEM instrument.

**Modal mineralogy:** The sample of Nakhla analysed in this study had approximate dimensions of 12mm x 6mm x 5mm. Such a sample, if prepared as standard thin sections (30µm thickness), would yield ~20 thin sections with a total area of ~1150 mm\textsuperscript{2}. A comprehensive survey of real thin sections of Nakhla was undertaken previously by [1]. They reported modal mineralogy of 12 thin sections from 9 different Nakhla stones, with a total area of 1192 mm\textsuperscript{2}, providing an excellent comparison for our dataset. Modal abundance of olivine reported by [1] ranged from 4.6vol% to 18 vol% between thin sections. Our CT dataset increase this range, from a minimum 1.98 vol% to a maximum of 19.62 vol%. This demonstrates that sample heterogeneity on even a mm scale must be considered in addition to heterogeneity between different fragments of the same meteorite fall. CT ‘slices’ of these extremes are shown in Figure 1.

**3D a necessity?:** Three dimensional characterisation of a sample is exceptionally useful for certain applications, but will represent an unnecessary step in many geochemical investigations. The aim of the present study is to analyse the carbon and oxygen isotope composition of individual carbonate and clay mineral assemblages at a high spatial resolution. Previous isotopic analyses of these mineral phases have generally been limited to bulk analyses [e.g. 2-8]. The advantage of in-situ isotope analyses would be greatly undermined by a biased dataset if the relationship between various veins is not understood.

**Alteration veins:** Minerals formed by aqueous processes are typically found in the nakhlite meteorites as veins within olivine grains. For example, the three large olivine grains in Figure 1b each have several...
veins of alteration, and there is at least one fracture which connects the three grains. Understanding the connections between veins from one olivine grain to the next is critical to interpreting any isotopic and chemical data. With intricate veining, formed by different generations of fluid, there may be comparable isotopic heterogeneities between different veins in a single olivine grain than between apparently different veins in several “unconnected” olivine grains. Only by characterising these alteration veins in three dimensions can the veining be fully understood.

C and O isotopes: Previous isotope analyses have revealed >40‰ variations in C and >15‰ variations in O between bulk carbonate in a suite of nakhlite meteorites [8]. There are significant variations in the abundance of secondary minerals and in the distribution and petrographic relationships in the different nakhlites [e.g. 9]. By analyzing individual mineral phases in specific sites of interest (e.g. various veins within olivine, pyroxene and mesostasis) we aim to understand more fully the variations between the nakhlites, and reconstruct the environment in which the aqueous alteration occurred.

The large variations in bulk carbonate suggest that variations in individual minerals will be similarly large.

Such variations are within the analytical capabilities of NanoSIMS. Spot to spot reproducibility for several carbonate standards is ±2.5‰ (2 s.d.) for δ¹³C (Fig. 3).

However, this reproducibility is on polished standards, and for delicate_precious samples it is often unsuitable to employ traditional polishing procedures; in the case of the nakhlites polishing may alter/remove the softer secondary minerals hosted within silicate grains. It has been demonstrated that sample topography can affect SIMS analyses by up to 4% for oxygen [10]. Topographic features are therefore removed or reduced using a focused ion beam. Data for secondary minerals in Nakhla, as well as true spot-to-spot reproducibility of real samples, will be discussed at the conference.

Future work: The preliminary analyses of Nakhla will provide a guide to future analyses of the nakhlites. The heterogeneity of mineral phases in different veins, and/or those formed during different episodes of aqueous activity, will provide a roadmap for analyses of other nakhlites. The utility of tomographic data will be demonstrated either as critical or not for understanding secondary mineral formation, and accurately reconstructing formation conditions. Further CT analyses will be performed if necessary.

Modeling will be undertaken to provide further details about temperature, pH, fluid chemistry etc. in which the various secondary minerals formed.

Conclusions: The nakhlite meteorites provide unique records of water flow on Mars. Accurate interpretation of these records can be achieved by high precision and high spatial resolution chemical and isotopic analyses. However, such analyses must be undertaken in a systematic and representative manner, avoiding sample bias and unintentional replication of analyses (e.g. through multiple analyses of a single continuous vein). The present study of Nakhla will serve as a unique demonstration of the potential benefits of combining three dimensional sample characterisation with isotopic analyses. Isotope analyses of other nakhlites (preceded by CT characterization if necessary) will be undertaken to identify the source of variation revealed in bulk carbonate analyses. These analyses will ultimately provide a much deeper understanding of aqueous processes on the surface and subsurface of Mars.