

HIGH RESOLUTION SCANNING ION IMAGING AND ANALYSIS OF SUBMICRON INCLUSIONS IN METEORITIC FORSTERITE. Ian M. Steele, Department of the Geophysical Sciences, Wendy Wolbach and Jan Chabala, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637.

**INTRODUCTION:** Forsterites with  $Mg/(Mg+Fe) > 0.99$  are relatively common within C3 and unequilibrated ordinary chondrites and often show unusually high levels of refractory elements including Al, Ca, Sc, V, and Ti (1,2). Inclusions within these grains are rare but electron probe traverses (e.g. Fig. 1) have shown enrichments in refractory elements at some points (3). BSE imaging shows no contrast suggesting a near-equal average atomic number to forsterite. Long exposure (10-15 minutes) x-ray maps have shown sub-micron inclusions, but chemical characterization has not been possible due to their fine size. From traverses such as Fig. 1, it can be seen that these inclusions are enriched in Ca and Ti in addition to Al, and have Fe nearly equal to the surrounding forsterite (~0.5 wt. % FeO). The level of Si and Mg can not be determined due their high levels in the surrounding forsterite and the relatively large excitation volume of the electron beam. Ion imaging using conventional ion microscopes has a spatial resolution approaching 1 micron which is not sufficient for characterization of these inclusions. Using a high lateral resolution (70nm) scanning ion microprobe at The University of Chicago (UCSIM), we imaged these inclusions to constrain their composition.

**ANALYTICAL INSTRUMENTATION:** The UCSIM utilizes a liquid metal ion source (Ga in our case) in which Ga liquid is drawn to a fine point source and Ga positive ions extracted to form a 40 keV primary ion beam of several tens of picoamps focussed to about 70nm. Positive (or negative) secondary ions are extracted with a low potential and focused to the entrance of a quadrupole mass analyzer with  $m/\Delta m$  of ~300. Images are obtained by scanning the primary beam with a selectable dwell time at each point and the resulting secondary ion signal recorded. To minimize variation of ion signals during sputtering, the quadrupole is set to different masses during alternate rows in the scan, forming a composite interlaced image. These images can then be separated to form two images with half the resolution in Y. These digital images are stored and intensities of individual pixels read to obtain relative secondary ion intensities. Important points are: 1) the primary current is small, precluding detection of some minor and most trace elements depending on their relative ease of ionization; 2) the mass resolution of the secondary ion analyzer precludes resolution of molecular interferences; 3) successive images from the same area often can not be obtained because of sample charging if the conductive coating has been altered in previous scans; 4) at any one analyses point in the scan, the dwell time is not sufficient for a steady-state ion yield to be established which will increase analytical uncertainty. With these limitations in mind, it should be possible to qualitatively identify inclusions within forsterite and in particular deduce the major element signature for possible phase identification.

**SAMPLES and IMAGES:** Inclusion-bearing forsterite was identified in a thin section of 84028,11 (C3V) by x-ray mapping of Al with the electron microprobe. One grain in particular (traverse shown in Fig. 1) had an especially high number of inclusions and all ion images were obtained from this grain. Interlaced images were obtained for pairs of elements with Al being the reference for each pair. In general, only one interlaced image could be collected from any one area before charging became severe.

As expected based on electron probe scans, there is a 1:1 correlation between Al and Ca images with an homogeneous background in the host forsterite. The separated Al-Ti images clearly showed inclusions on the Al image but no contrast was apparent in the Ti image probably because the concentration is low and Ti does not have as high an ion yield as Al, therefore reducing its sensitivity. The major elements of forsterite, Mg and Si, are particularly interesting and image pairs for Al-Mg and Al-Si were obtained. The Si image was very homogeneous and inclusions represented on the Al image did not appear as brighter or darker areas on the Si image. This suggests that the inclusions are silicates as opposed to oxide phases such as spinel or hibonite which might be expected to be early crystallization (condensation) or exsolution products with forsterite. The Mg image is not conclusive but in many cases where Al clearly indicates an inclusion, there is a corresponding deficit of Mg relative to forsterite and in a few cases a dark spot indicating essentially no Mg. This variation suggests variable Mg within the inclusions. The Na-Al image pairs are complex, sometimes showing Na with no matching Al, Al with no

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matching Na, and sometimes both elements. Because all Na, Na/Al, and Al areas are approximately the same size, surface contamination is considered unlikely. Like Mg, this variability suggests a variable Na concentration and suggests that some inclusions may be predominately Na-Si-Mg and others Ca-Al-Si-Mg. The table summarizes the inclusion chemistry based on these images and electron probe scans:

Table. Some chemical features of inclusions within forsterite.

Si-	Present in all inclusions at levels similar to forsterite.	Mg-	Variable concentration (0 to high).
Al-	Present in most inclusions at near constant level.	Ti-	Present, but a minor element.
Na-	Present in some inclusions where Al is absent.	Ca-	Strongly correlated with Al.
Fe-	Present at same level as forsterite (0.5% FeO).		

Quantitative analysis from these images would be possible if matrix effects were known, but these are not known for this instrument. Estimates for some elements can be made based on the forsterite where Ca, Si, and Al concentrations are known and with the assumption of no differential matrix effects. For Al the relative intensity of Al for inclusions:forsterite is 67:0.75. The measured Al concentration in the forsterite is 0.25%  $\text{Al}_2\text{O}_3$ , giving an  $\text{Al}_2\text{O}_3$  concentration in the inclusions of 22%. A similar calculation for Ca gives  $72/10 \times 0.75$  or 5.5% CaO. Assuming  $\text{SiO}_2$  to be near 50%, a total is obtained near 80%. The discrepancy from 100% could easily be due to matrix factors other than the 1.0 values assumed and the lack of data for Na, Mg and other minor elements.

**SUMMARY:** The identification of the inclusion phase is not certain, but is a silicate. The low Ti rules out fassaite, the very high Al rules out forsterite, the presence of Mg rules out feldspar. The variable Mg and especially Na is a characteristic found in a common phase in these meteorites which is probably vitreous as the composition of these other occurrences matches no mineral. Glass inclusions have been previously reported in other meteoritic olivines (4) and are common in terrestrial olivines. Tentatively we conclude that the inclusions are glass. An important point is whether they represent trapped liquid as with terrestrial occurrences or whether other processes such as liquid condensation could produce these features. In any case, the scanning ion microprobe appears to be a unique instrument for determining the major element chemistry qualitatively and, with additional effort to determine matrix effects for a small set of elements, quantitative compositions for these and other submicron phases.

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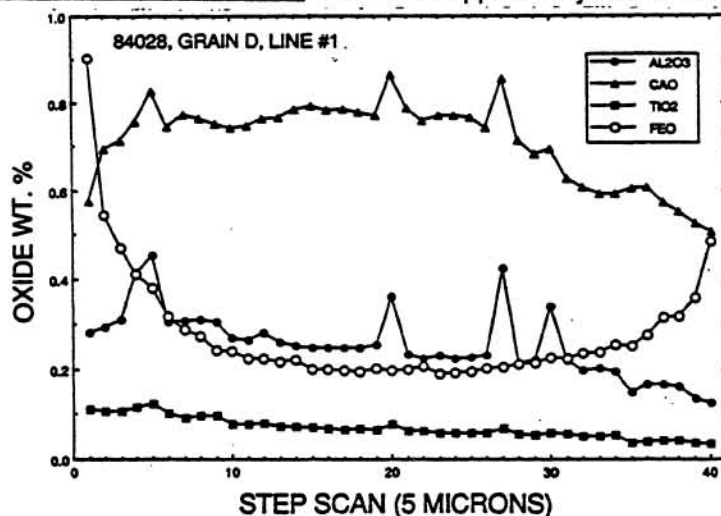


Fig. 1. Step scan across forsterite grain in 84028,11. Step interval is 5  $\mu\text{m}$ . Scan crosses several inclusions as indicated by correlated spikes in Ca, Al and Ti concentrations. No variation is apparent in Fe trend.