MULTISCALE ABUNDANCE AND SIZE DISTRIBUTION OF INCLUSIONS IN THE ALLENDE CV3 METEORITE BY X-RAY IMAGE ANALYSIS OF SLABS. D. S. Ebel[1,4], C. E. Brunner[2,5], and M. K. Weisberg[1,3,6]. [1]Department of Earth and Planetary Sciences, American Museum of Natural History, Central Park West at 79th St., New York, NY 10024, [2]Western Kentucky University, 1906 College Heights Blvd., Bowling Green, KY 42101. [3]Dept. of Physical Sciences, Kingsborough College, City University of New York, Brooklyn, NY 11235. [3](debel@amnh.org), [5](chelsea.brunner@wku.edu), [6](mweisberg@kbcc.cuny.edu).

Introduction: Carbonaceous chondrites such as Allende (CV3) resulted from accretion of an early generation of solids formed in the solar nebula or protoplanetary disk. These solid components (clasts) are: Ca-, Al-rich inclusions (CAIs [1]), chondrules, amoeboid olivine aggregates (AOAs [2-4]), and darker lithic fragments (dark inclusions) of primitive meteoritic material (DIs). Their relative abundances are primary data that informs and constrains theories of their origin and relevance to planet formation [1], for example, the hypothesis of 'complementarity' [5-6], and will be important for in situ resource utilization in exploration.

McSween [7] reported the abundances of chondrules (including mineral - isolated olivine, IOL - and lithic fragments), refractory inclusions (including both AOAs and CAIs), Fe-Ni metal, and matrix from point counting of polished CV thin sections, determining clasts by reflected and transmitted petrographic microscopy, the best method then available. These abundances are the root data for many tables published ever since [e.g. 8]. The present study is motivated by the need for accurate CAI abundances (L. Grossman, pers. comm., Gatlinberg 2005), and the statement in [7] that "more accurate modes could be obtained from large slabs", which were not available.

It has long been recognized that Allende and other CVs have remarkably high abundances of CAIs compared to other chondrites. However the macroscopic view of Allende can be misleading. In hand sample, there are some round, and many more irregular white objects (1mm – 1cm in diameter) that create the illusion of a high abundance of CAIs. In fact many of these are forsterite-rich objects. Although the abundances of Ca, Al, Ti and other refractory elements is slightly higher in CV than in other chondrite types [9,10], relative to Si, it is not clear whether this results from over-representation of CAIs [11].

Methods: Random cut slabs of Allende were selected from the AMNH collection, and cut to fit our 5.5 x 4 cm electron microprobe (EMP) sample holder, and polished for x-ray mapping. Additional polished thick (PS) and thin (PTS) sections were also mapped [7]. Surfaces were mapped in Si, Fe, Ca, Al, Mg (WDS) and S, Ni, and Ti or Mn (EDS) using fixed-beam, stage-motion mapping at 13, 5, or 4 μm/pixel resolution (Table 1). Maps were stitched into seamless mosaics, and element, BSE, and RGB composite (Fig. 1) maps were superposed as layers in a drawing program to allow masking, manual outlining of inclusions, and determination of inclusion type.

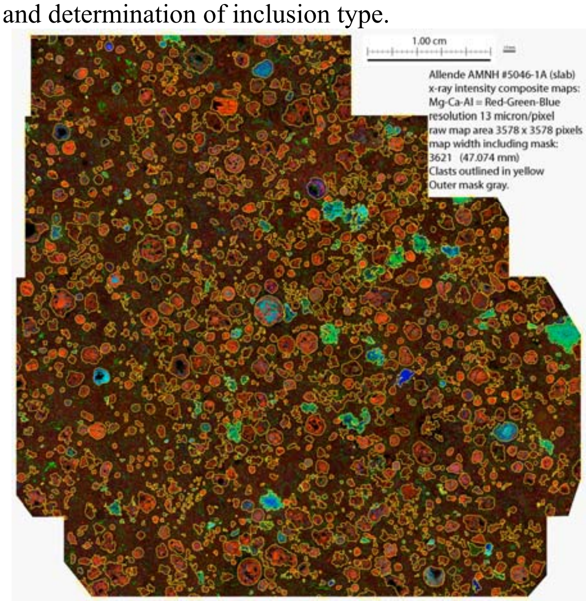

Fig. 1: Mg-Ca-Al composite x-ray mapping of slab 5046-1A, with clasts outlined in yellow.

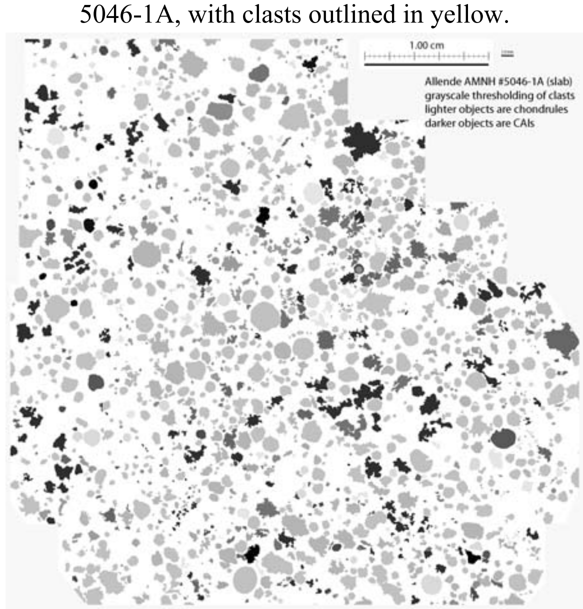

Fig. 2: Grayscale-coded clast output that is input into pixel-counting software.

Hand-drawn inclusion outlines - the critical step, and determination of inclusion type, have been checked by all authors independently on 1 slab and 2 PS, for a total area of ~19 cm^2 (Table 1). Chondrules (PP, PO, POP, BO, RP), CAIs (CTA, FTA, B, misc) and other components were grayscale-coded (Fig. 2) and the results output at a resolution to oversample the input EMP data. Software in IDL was written to count the numbers of pixels representing inclusions of each type, in each map image. Size distributions and other quantities were also collected from the inclusion map data, using the 'analyze particles' feature of the ImageJ program, on binary thresholded output such as Fig. 3.

Table 1: Area% components, compared to [7].

Sample:	5046-1A	AL2ps1	AL2ps5	average	ref[7]
Matrix+Lithics	67.99	58.87	63.89	63.58	38.4
CAI+AOA	7.12	8.58	7.54	7.75	12.6
Chondrule+IOL	24.89	32.55	28.56	28.67	45.9
Fe-Ni	0	0	0	0	3.1
AOA	3.87	5.03	2.56	3.82	3.2
sample type:	slab	PS	PS		PS
EMP res (mu/pxl):	13	4	5	total	
area (mm^2):	1790	39.30	88.93	1918.2	
area EMP pxls:	10590932	2457473	3557199	21382034	1572

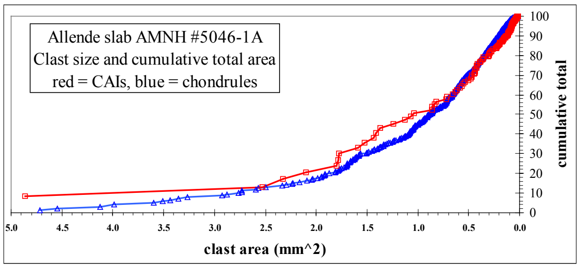

Fig. 3: Size distributions of chondrules and CAIs.

Results: Figure 1 illustrates an Mg-Ca-Al composite map of slab AMNH #5046-1A, with the drawn outlines of CAIs, AOAs. In Fig. 2 each clast type is coded with a fill grayscale. From this result, pixel counts and size fractions can be obtained using customized or canned software. This method allows robust reporting of area fraction, size distributions, and overall abundances of each clast type in the sample suite. Sufficient data from Allende were obtained so that independent analysis of a section outside the dataset yielded a similar result. Results and sample data are presented in Table 1, grouped into the categories of [7, Table 2], with %AOA presented separately.

Fig. 3 illustrates size distributions calculated for the slab results, omitting AOAs. The upper curve (CAIs, red squares) and the lower curve (chondrules, blue triangles) are roughly coincident. Large CAIs accounts for more of the CAI area than large chondrules do for the chondrule area, and a larger fraction of CAIs than chondrules is between 0.5 and 1.75 mm^2 in area.

Discussion: Our findings are broadly consistent with those of [7], except that matrix is ~50% more abundant in our result, with a correspondingly lower abundance of chondrules and CAIs. We did not count metal, which is very rare in Allende. This difference is likely due to different objective criteria used in the studies, and biases introduced by the techniques themselves. In petrographic point counting, the sharp change in grain size between transparent clasts and opaque (fine-grained) matrix defines boundaries. In x-ray and BSE maps, the accretionary rims on many chondrules appear similar to, and were preferentially included as matrix. A problem in determination of modal abundances is the interpretation of chondrule rim material. It may be interpreted as accretionary, added post-chondrule formation, or as the original outer chondrule margin prior to parent body alteration. It is also likely that the abundance of small chondrule and CAI fragments in matrix is under-determined by our technique. To account for small chondrule and CAI fragments in the matrix below 5 µm resolution, we plan to map matrix areas at 1 µm/pxl resolution, and use the results to subdivide the 'matrix' determined at coarser resolution, so that the total abundance of CAI- and chondrule-like inclusions can be calculated with rigor.

Our results provide a more robust count than [7] of the relative abundances of AOAs and CAIs in Allende. AOAs are slightly more abundant than CAIs in Allende, as noted by [8], and CAIs are <4.8%, consistent with [11]. Our findings underscore the importance of AOAs to the origin of meteoritic chondrules [2-4].

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