Visualisation and quantification of CV chondrites using micro-tomography.

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Abstract

Tomography is a non-destructive technique that allows to study the 3D petrography of meteorites. There are two major objectives: an instructive visualisation of the meteorite and quantification of its components. While excellent software for visualisation is available, quantification remains difficult. We use a commercial software for visualisation and a software tool we recently developed (PhaseQuant) for quantification. We studied the two CV chondrites Allende and Mokoia. A set of provided movies details their 3D petrography. Component modal abundances agree with previous reports and modal abundance differences between Allende and Mokoia support the chondrule-matrix complementarity and that chondrules and matrix formed from the same chemical reservoir. We find two types of chondrules, a normal type and one where a normal type I or II chondrule is almost completely encapsulated with an opaque-rich layer. This layer was probably acquired during a late stage condensation process. The appearance of opaques in chondrules and matrix is different, not supporting a genetic relationships between these. Low abundances of compound chondrules (1.75 vol.% in Allende and 2.50 vol.% in Mokoia) indicate low chondrule densities/low relative component velocities in chondrule formation regions. Porosities on a scale <10-20 µm allowed for only local aqueous alteration processes on the meteorite parent bodies.
1. Introduction

Computer aided tomography (CT) allows the non-destructive study of the 3D petrography of meteorites. There are two major goals we want to achieve: (i) an informative 3D visualisation of the meteorite and (ii) the quantification of its 3D petrography. Many problems in cosmochemistry require accurate petrographic information that cannot or only insufficiently be obtained from 2D sections. The rapid development of 3D tomography in recent years allows to acquire such information with good accuracy and precision. The major difficulty that needs resolving, is the quantification of tomographic data sets.

Pioneering work of quantifying tomographic meteorite data has been done by Ebel and Rivers (2007), Friedrich (2008) and Griffin et al. (2011). Their solutions are, however, not available as easy to use program interfaces. A group at the University of Texas at Austin developed the ‘Blob3D’ software with a graphical user interface that is applicable to rock samples (e.g. Ketcham 2005). This program is written using the commercial IDL software language and is, hence, not easily expandable. An example for a commercial solution we are using, but with no possibilities to expand or problem tailor it, is VGStudio Max.

As a consequence, we decided to develop a new software tool to quantify meteoritic data (Elangovan et al., in revisions). This software is called ‘PhaseQuant’ and is a tool with a ready to use graphical user interface, freely available and easily expandable. Technically, PhaseQuant is a plugin for the ImageJ software, which is a powerful and platform independent (Java-based), widely adopted public domain image-processing program that is developed and maintained by the US National Institutes of Health\textsuperscript{1}. PhaseQuant works seamlessly alongside all other ImageJ tools and plugins.

Here we study the 3D structure and petrography of Allende (CV3.7) and Mokoia

\footnote{http://rsbweb.nih.gov/ij/}
(CV3.6). Allende is one of the best-studied meteorites and is therefore an ideal starting point to visualise and quantify meteorite 3D structures. To better rank the results of Allende, we compare it to the 3D petrography of Mokoia. We use PhaseQuant to visualise and quantify the tomographic data, but apply VGStudio Max for sophisticated visualisations.

2. Technique

2.1 μ-CT measurements

A computer-aided tomography scanner consists of (i) the scanner that obtains thousands of individual radiographs while the sample rotates on a turntable and (ii) a computer that calculates from all the radiographs a 3D reconstruction of the sample.

The samples were scanned with a cabinet-based Nikon Metrology HMX ST 225 micro-CT scanner. The X-ray source produces a polychromatic beam and was operated in the range of 120-160 kV acceleration voltage and 60-100 µA current, depending on the transmission through the sample. This is primarily a function of the sample size: a bigger sample requires higher kV/µA/exposure. X-ray transmission was recorded on a 2000x2000 pixel Perkin Elmer XRD 1621 AN3 HS detector panel with a 16 bit pixel depth. Voxel edge length of the samples was 11.3 µm for Allende and 7.2 µm for Mokoia. Reconstruction of the radial projection images into a stack of serial slices was carried out using the cone-beam, back-projection algorithms in the CT-Pro software by Nikon Metrology. Beam hardening was corrected for using an algorithm built in the reconstruction software. The results were exported as a stack of images in dicom format, which is widely used and a quasi standard format for tomographic data.

Data processing was carried out on workstations with up to 96 GB RAM, as the
individual data files have sizes in the range of 20-32 GB. The final computer reconstruction consists of cubic voxels - the 3D equivalent of pixels. A voxel consists of 4 parameters, its x,y,z-coordinates and its grey value. The range of possible grey values depends on the bit depth of the detector panel (in this case 65,536). Here we refer to the computer reconstruction as the raw data set.

2.2 Visualisation and quantification

A major difficulty of industrial cabinet-based CT scanners is their polychromatic X-ray source. As a mineral attenuates different wavelengths of a polychromatic X-ray beam differently, the final intensities of two different minerals or components recorded on the detector panel can be very similar, and, hence, peaks of different minerals will overlap in the density plot (Fig. 1). This is further complicated as many minerals are part of solid solution series with the heavy X-ray absorber Fe forming one of the end-members. Small differences in Fe-content can cause significant changes in X-ray attenuation, which adds to the problem of peak overlap. Finally, more than one mineral maybe recorded in a single voxel, so its grey value actually represents two or more minerals (‘partial volume averaging’) (cf. McColl et al. 2006). Such voxels plot somewhere between the two phases or components in the density plot. The overlap of density peaks and the partial volume averaging represent the biggest hurdle in quantifying tomographic data so far.

The first step of processing the raw data requires the decision, which voxels represents which phase or component. Once this is done, it is easy to quantify the data set. However, the sheer size of the raw data prohibits doing this by hand. The conventional method is to manually frame ranges of grey values and assign these to the different phases and components. This process of defining density boundaries for the different materials is known
as ‘thresholding’ and provides a good approximation. However, setting the thresholds is subjective and has a comparatively large error. Nearly all software for quantifying tomographic data is based on thresholding as the decision mechanism which grey value represents which phase/component.

The PhaseQuant\textsuperscript{2} program (Fig. 1) we use here has a more sophisticated decision engine that is not based on thresholding and, hence, allows for a more objective and reproducible segmentation of the raw data. PhaseQuant makes a statistical analyses of the voxels surrounding each voxel to decide which phase/component the voxel in the centre represents. From this, PhaseQuant draws a schematic 3D model of the meteorite. This is illustrated in Fig. 2, which displays a slice of the raw data alongside the same slice of the schematic 3D model. A technical description how the decision engine of PhaseQuant works is presented in Elangovan et al. (in revisions).

There are currently two major limitations using PhaseQuant - or any other decision engine. It is not possible to automatically distinguish between type I and type II chondrules, although these can be told apart on the raw data (cf. the annotated movies in the electronic annex). The density of type II chondrules is almost indistinguishable from matrix and, hence, is currently counted as matrix. Something similar happens with CAIs. These have almost the same density as chondrules and are therefore recognised as chondrules by PhaseQuant. A number of objects seen in the raw data are comparatively large, opaque free and have rather irregular outlines. These are probably the CAIs. In future iterations of PhaseQuant it is intended to use these features to separate chondrules from CAIs. Finally, troilite and magnetite have similar densities and are currently grouped together when separating these two opaques from metal.

\textsuperscript{2}Check www.cosmoprograms.com for the PhaseQuant plugin, manual, updates and user feedback options.
PhaseQuant can only segment two different phases at a time. First, a density range needs to be specified that PhaseQuant will then automatically segment in two components. Such thresholding can be done to first separate chondrules, CAIs and matrix (i.e. silicates and oxides) from opaque phases. PhaseQuant then operates only on the silicate/oxide range to segment chondrules/CAIs from matrix. Then it operates on the opaque range to separate sulphide/magnetite from metal.

The accuracy of PhaseQuant can be determined by comparing it to ground truth data. These are obtained by choosing one or more individual tomographic slices on which the different components are manually segmented (Fig. 2). These are fed into PhaseQuant, which automatically compares them to its own results. PhaseQuant produces an error map (Fig. 3), highlighting the differences of the ground truth and its own segmentation. We used this technique to determine the error for the data we present here, which is about 10 rel. %.

The schematic 3D model is used to extract quantitative data. We use PhaseQuant to determine detailed modal abundances. Size and spatial distributions can in principle be extracted as well, however, not all technical necessities could yet be resolved satisfactorily. We note that the petrography of different chondrite groups is highly diverse. PhaseQuant is currently optimised for CV chondrites.

3. Results

We studied two CV chondrites, Allende and Mokoia. Figure 4 compares a slice of the raw data to its corresponding electron microscope image, illustrating the amount of detail that is achievable with current cabinet-based scanners. Chondrules, matrix and opaque phases can be easily distinguished and also the internal structure of individual chondrules and other
components is visible. The electronic annex contains a collection of videos (movies 1-7) and
images (Fig. A1-A4) displaying detailed 3D structures of the samples.

Allende and Mokoia have been studied since a long time in 2D sections (e.g. McSween, 1977; Brearley & Jones, 1998) and their general petrography is well known. In the following we focus on 3D petrographic features that are difficult or impossible to obtain from 2D sections. Movies with annotations highlighting the features mentioned in the following can be found in the electronic annex (movies 4 & 7).

3.1. Visualisation

**Allende**

The Allende sample has 455 mm$^3$ (cube equivalent edge length: 7.7 mm) and includes around 400 chondrules and CAIs, obtained from visual counting using the raw data set. It is difficult to provide an exact number, as it is not always clear whether an object really is a chondrule or some sort of fragment.

The raw data show that Allende has almost no cracks and no visible porosity. The overall texture is homogeneous, i.e. individual components such as chondrules and CAIs are usually not elongated, aligned or display any kind of regular pattern.

The chondrules and CAIs occasionally contain cracks. Many have a noticeable abundance of pores or holes, indicating that in 2D sections holes in chondrules are not necessarily the result of preparation, but a real feature. The modal abundance of holes in a single chondrule is, however, usually below ~1 vol%. Most chondrules and CAIs are intact, only few fragments exist.

There are two types of chondrules that so far have not been sufficiently recognised as such. These are best identified in stereographic images and movies (Fig. 5; movies 2 & 3). In
the first type, the chondrule is almost spherical with no additional layer surrounding it. In the second type, the chondrule is almost completely encapsulated by a layer of opaques. This layer or rim usually has an irregular outline and additional shells of opaques may occur inside it (cf. movie 3). These chondrules are in many cases significantly bigger than the first type. The chondrule inside the layer is of the normal first type and can be either a type I or a type II chondrule. We designate these simply as ‘opaque-layered chondrules’ and the other as ‘normal chondrules’. It is trivial to state that these two types of chondrules have different bulk compositions and must have had different formation histories. About a quarter of all chondrules in Allende are opaque-layered chondrules.

Despite there are around 400 chondrules and CAIs in the sample, we found only 7 compound chondrules. There are also only few chondrules and CAIs in direct contact with each other. Between almost all is still a layer of matrix.

Most opaques occur in chondrules, only few in the matrix. The major occurrence of opaques is as small blebs peppered throughout the rim of the opaque-layered chondrules. A minor occurrence is as larger, but much fewer, blebs inside chondrules. A second minor occurrence is in matrix, where opaques only occasionally occur, but then can in cases be rather large. Opaques in matrix have often elongated and irregular shapes, no dominant type of shape can be identified. In addition, it is known from electron microscopy that opaques occur as μm-sized grains inside the matrix, but these are below the resolution of our scans.

The matrix of Allende appears largely homogeneous. At the current density resolution, no immediately visible gradients from chondrules into regions dominated by matrix are observed.

*Mokoia*
The Mokoia sample has 452.7 mm³ (cube equivalent edge length: 7.7 mm) and includes nearly 400 chondrules and CAIs. Despite the same volume and nearly same amount of chondrules and CAIs, the chondrule and CAI density in Mokoia is visibly higher than in Allende.

Mokoia contains much more cracks than Allende. Some run through matrix and chondrules, whereas other chondrules are completely unaffected by cracks, and cracks actually terminate or originate at or from the surface of these.

Chondrules have internal cracks that do not continue into the surrounding matrix. Although a few chondrules contain tiny holes, chondrule porosity appears to be much less frequent than in Allende, approaching almost zero.

In Mokoia, more than half of all chondrules are opaque-layered chondrules. However, their appearance is often very different from the ones in Allende. The opaque-layer is of variable thickness among chondrules, and a number of chondrules consist entirely of opaque-layer material, without a detectable inner chondrule. When the layer is very thick, it might better be described as a rim peppered with opaques. In this case, the rim is highly irregular and has a density close to the matrix (cf. movie 7). This kind of rim appearance is not seen in Allende. There seems to be a transition from chondrules without layer, through opaque-layered chondrules with variable layer thicknesses to chondrules completely consisting of what forms the layer of the opaque-layered chondrules.

Similar to Allende, the vast majority of chondrules is intact, only few objects can be classified as fragments. We found 10 compound chondrules in Mokoia, a slightly higher percentage than in Allende (2.5% vs. 1.75%). Most chondrules and CAIs in Mokoia are not in direct contact with each other.

The major occurrence of opaques is as part of the layers surrounding opaque-layered chondrules. A more minor, but still significant occurrence is as larger blebs inside chondrules
and in the matrix, where opaques can in cases be very large, up to almost 1.5 mm long. No comparable sized opaques occur within chondrules. There is no typical shape of opaques within the matrix, they are all somewhat oval or irregular. Again, it is known from electron microscopy of sections that μm sized opaques occur in the matrix.

The Mokoia matrix is as the Allende matrix mostly homogeneous. In one region, we found a gradient, indicating at least some zonation (movie 7).

3.2. Quantification

Allende

Table 1 lists 3D modal abundances determined from the schematic 3D model and using PhaseQuant. Modal abundances from 2D sections can be inaccurate when too small samples are chosen. This is especially problematic for components with low modal abundances such as opaques (Hezel et al. 2008). Ebel et al. (2009) determined modal abundances from a very large (121 cm$^2$) Allende slab using X-ray image analysis. These are probably the most accurate 2D modal abundances for Allende to date. We measured a combined chondrule + CAI abundance of 35.07 vol.% and a matrix abundance of 63.07 vol. %. Ebel et al. (2009) report a combined chondrule + CAI abundance of 38.30 vol% and a matrix abundance of 61.47 vol%. This underpins that PhaseQuant determines correct modal abundances. However, PhaseQuant’s 1.78 vol.% of opaque phases are an order of magnitude higher than what Ebel et al. (2009) report for opaque phases (0.18 vol.%). Accurate modal abundances of opaque phases are difficult to obtain from 2D sections, as these are a minor component (Hezel et al. 2008). When looking at the movies of the tomographic data, it seems Ebel et al. (2009) underestimated the opaque modal abundances. We note, however, that partial volume averaging could lead to some overestimation of our result - on the other hand,
we certainly miss part of the μm-sized opaques in the matrix. This needs to be studied further in detail using small samples and high spatial resolution.

One of the advantages of PhaseQuant are itemised modal abundances. Table 1 lists modal abundances for sulphide and metal not only separately, but also depending on whether they occur in chondrules or matrix. It appears that opaque phases are about two times more abundant in chondrules than in matrix, when factoring in the lower modal abundance of chondrules than matrix. Metal seems to be even more dominant in chondrules than in matrix. The porosity of Allende is very low, as expected from the absence of any cracks in the sample.

Mokoia

The results for Mokoia are similar to Allende (Table 1). Table 2 lists our results compared to data reported by Ebel et al. (2009). For Mokoia, Ebel et al. (2009) used a section of 0.84 cm$^2$, which is a typical size for such studies, and nearly 150 times smaller than the area they used for Allende. Mokoia has a higher chondrule and a lower matrix abundance than Allende. This is already obvious from a comparison of the raw data (movies 1,4,6,7). Opaque modal abundances as well as their sizes and distribution are similar to Allende. Most opaques occur in the rims of Mokoia, a smaller abundance within the normal chondrules. The porosity in Mokoia is significantly higher than in Allende (0.08 vol.% vs. 2.23 vol.%), which is because of the higher abundance of cracks in Mokoia than in Allende.

4. Discussion

Both, Allende and Mokoia have a homogeneous overall texture with no elongation of chondrules or apparent pattern of their different components, indicating a homogeneous
agglomeration of their parent bodies as well as a homogenous parent body compaction regime. Allende lacks any obvious cracks. Individual chondrules in Allende contain cracks, which are most probably the result of volume reduction during chondrule crystallisation. The absence of cracks results in the low overall porosity of 0.08 vol.%. This is much lower than the 23±5% porosity reported for Allende by Consolmagno et al. (2008). This discrepancy is most probably due to the resolution of our scan (cf. Friedrich & Rivers, this volume), which means that most of the porosity reported by Consolmagno et al. (2008) is on a scale <10-20 μm. This small scale might explain why Corrigan et al. (1997) found a low permeability for Allende despite the large bulk porosity. The low permeabilities do not allow for large scale fluid flow on the Allende parent body and any alterations must have been restricted to a very local domain. Mokoia contains more cracks and we measured a porosity of 2.23 vol.%. Again, this is much lower than the bulk porosity of 24% determined by Corrigan et al. (1997). There are no permeability data for Mokoia. Mokoia experienced a somewhat larger degree of aqueous alteration than Allende (e.g. Krot et al., 1995,1998; Tomeoka & Buseck 1990; Brearley, 2003), however, this was probably equally restricted to a very local scale. There is no evidence for previous crack generations in either of the meteorites that was healed during an aqueous alteration event and that might have allowed for larger scale aqueous alteration processes.

Some cracks in Mokoia terminate/originate at/from the surface of chondrules. These chondrules were rigid enough to withstand the event forming the cracks, indicating that the energy involved was not extensive and only affected already structurally weakened chondrules. The cracks are a post-accretion feature, as some run through matrix and chondrules. None of the cracks are filled with any kind of precipitates. Aqueous alteration on the Mokoia parent body must have predated crack formation.
It is unexpected that individual chondrules, predominantly in Allende contain comparatively large porosities. These are real features and not polishing artefacts of section preparation - although these might occur as well. The porosities are in cases comparatively large and it seems unlikely these are the result of volume reduction during crystallisation. Such large porosities are not commonly observed in igneous rocks. It is therefore possible that the porosities are remnants of the porous chondrule precursor aggregates. High-resolution scans are required to study this in detail. If the porosities are in fact remnants of the precursor aggregates, these would provide a rare and important opportunity of insight to chondrule precursors, especially when comparing different chondrite groups.

The stereographic images of Allende reveal two types of chondrules that have so far insufficiently been recognised: opaque-layered and normal chondrules. The opaque-layered chondrules contain normal chondrules of type I or II. This rules out that the opaques result from the reduction of type II chondrules (Connolly et al. 1994). It is also clear that opaque-layered and normal chondrules must have different formation histories. Opaque-layered chondrules, especially in Mokoia, often have multiple layers of opaques and silicates or rims peppered with opaques, respectively. The rim is patchy and irregular, whereas the inner chondrule is a normal chondrule. We propose that a fraction of chondrules in Allende and Mokoia experienced a second formation stage at lower temperatures in which they aggregated an irregular layer of opaques and silicates. This fraction is higher for Mokoia than for Allende. Such a scenario is in accordance to similar findings for other meteorites by Tissandier et al. (2002) and Hezel et al. (2003). The normal chondrules might represent another generation of chondrules that did not experience this second stage. It has been shown previously that chondrule formation occurred repeatedly (e.g. Jones et al. 2005), although no more than 2-3 cycles are possible (Hezel & Palme 2007). We exclude a parent body formation of the rims, as these contain much higher modal abundances of opaques than the matrix.
Chondrules in Allende as well as in Mokoia contain about twice the amount of opaques than the matrix. Most opaques occur in the opaque-layer around chondrules and occasionally inside the normal chondrules. None of these opaques are usually larger than a few tens to hundreds of \( \mu \text{m} \). Opaques in the matrix occur either as \( \mu \text{m} \)-sized grains that are not resolved by our scans or as large grains, up to 1.5 mm in size. The dichotomy in size between opaques in chondrules and the matrix excludes a formation of opaques inside chondrules and then separation of them from the chondrules. Such a scenario has been proposed for CR chondrites by Connolly et al. (2001) and theoretically studied by Uesugi et al. (2008). A formation of the opaques by e.g. condensation in the nebula seems difficult to achieve. Opaques are a minor component in the matrix and as such many small opaques would be expected from condensation rather than few very large ones. Even if sulphides in the matrix represented the small-sized fraction, the size distribution of such a condensate population would not allow for the few very large opaques found in the matrix.

Hezel & Palme (2010) demonstrated that the average Mg/Si ratio of bulk chondrules (high Mg/Si) and matrix (low Mg/Si) in carbonaceous chondrites is complementary and their bulk Mg/Si is CI chondritic. They used this observation to show that chondrules and matrix must have formed from a common reservoir. Allende and Mokoia have different component modal abundances. Allende has a higher matrix (63.07 vol.% compared to 53.29 vol.%) and a lower chondrule & CAI modal abundance than Mokoia (35.07 vol.% compared to 40.04 vol.%). Hezel & Palme (2010) explain the formation of the complementarity by a preferential incorporation of the high-temperature condensate forsteritic olivine into chondrules. If this is true, the Mg/Si ratio of matrix in meteorites with low matrix modal abundance should be low, and the Mg/Si ratio of average chondrules high. Mokoia has a lower matrix modal abundance than Allende as well as a lower Mg/Si ratio than Allende (0.78 compared to 0.88; Kimura & Ikeda, 1998). This agrees with the expectation and further strengthens the hypothesis that
chondrules and matrix of carbonaceous chondrites formed from the same reservoir, i.e. together in the same nebula region.

Compound chondrules provide important insights to the formation conditions of chondrules (e.g. Gooding & Keil, 1981; Wasson et al., 1995; Sekiya & Nakamura, 1996; Ciesla et al., 2004; Akaki & Nakamura, 2005; Miura et al., 2008). One such important parameter is the number of compound chondrules, which can only be measured from 2D sections when large areas are studied (Hezel et al., 2008). Akaki & Nakamura (2005) did this and studied 100 thin sections from the two CV chondrites Allende (36 cm$^2$) and Axtell (6 cm$^2$). They found that 1.4% of the chondrules are compound chondrules. This agrees well with our result of about 1.75%. The low abundance demonstrates that chondrules did not collide frequently when they were still molten. Chondrule densities or relative chondrule velocities must have been low during their formation. This is in accordance with only few fragments and usually intact chondrules. The compound chondrule abundance in Mokoia is about 42% higher than in Allende, indicating a higher chondrule density, as is apparent from the 3D petrography.

5. Conclusions

The 3D visualisation and quantification of bulk Allende and Mokoia provide a unique insight to the structure of these meteorites. Tomography allows this insight while keeping the sample entirely intact and undamaged. It is desirable to obtain similar structural datasets for other meteorites, especially of rare, precious or inaccessible specimens, for which this technique is ideal.

The different Mg/Si ratios of chondrules and matrix and different chondrule and matrix abundances of Allende and Mokoia underpin the idea that both components formed
from the same nebula region. The low abundance of compound chondrules, and the few fragments point to a comparatively low chondrule abundance and/or low relative chondrule velocities in their formation region. The distribution of chondrules and CAIs show that the meteorite parent bodies agglomerated homogeneously and had a homogeneous compaction regime. The porosity of the parent body was on a scale $<10-20 \mu$m making it rather impermeable to large scale aqueous alteration. There is no other evidence for large scale aqueous alteration. Normal chondrules had a different formation history than opaque-layered chondrules. The latter obtained a rim of silicate and opaques, maybe at lower temperatures when sulphides started to condense. The formation of large grains of opaques is puzzling. We exclude their formation in and later ejection from chondrules. Their large sizes in matrix make a direct condensation origin equally unlikely.
Acknowledgements

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References


distribution of inclusions in CV3 chondrites by X-ray image analysis (abstract). 40.

*Lunar and Planetary Science Conference #2065.*

(in revisions).

Friedrich J. M. (2008) Quantitative methods for three-dimensional comparison and

volume.

Gooding J. L. and Keil K. (1981) Relative abundances of chondrule primary textural types in
ordinary chondrites and their bearing on conditions of chondrule formation. *Meteoritics*
**16**, 17-43.

Griffin L., Elangovan P., Mundell A. and Hezel D. C. (2011) Improved segmentation of
chondrules from micro-CT images of meteorites using local histograms. *Comput. &
Geosci.* (in press).


Sci.* **38**, 1199-1216.


### Tables

Table 1: Modal abundances of CV chondrite components obtained in this study (vol.%).

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<th>Allende</th>
<th>Mokoia</th>
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<td>in matrix</td>
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\(^1\)Fraction of chondrules & CAIs in \%.

Table 2: Comparison of chondrite component modal abundances of this study (vol.%) to data reported by Ebel et al. (2009) (area%).

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<td>Total</td>
<td>100.00</td>
<td>99.95</td>
<td>100.00</td>
<td>99.96</td>
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</tbody>
</table>
Figures

Fig. 1

Fig. 2
Fig. 3

Fig. 4
Fig. 5
Figure captions

Fig. 1: The graphical user interface of PhaseQuant. The density plot is displayed in the working area. The grey value of the voxels, primarily representing a certain density, is plotted along the x-axis. The number of voxels with the same grey value is plotted along the y-axis. The large overlap of matrix and chondrules/CAIs is obvious.

Fig. 2: Comparison of an Allende slice of raw data with the same slice of the schematic 3D model produced by PhaseQuant and the ground truth data. Parts of few chondrules have grey values close to the grey values of the matrix and are missed by PhaseQuant.

Fig. 3: Error map of an Allende slice: A slice of the schematic 3D model is compared to ground truth data determined from the corresponding raw data slice. The lighter grey marks the areas where the schematic 3D model and ground truth data do not agree. These error maps are used to choose the best method of segmentation in PhaseQuant.

Fig. 4: A slice through Allende obtained using tomography and electron microscopy. The comparison illustrates the level of detail achievable with current cabinet-based scanners. Note that the two images are not exact matches, as it is extremely difficult to find a particular slice in the tomographic volume.

Fig. 5: Stereographic image of Allende (red/green glasses required). Shown are chondrules/CAIs and opaques. Opaques are slightly more light yellow. The empty space is matrix. An opaque-layered chondrule can be seen in the central upper part. Additional stereographic images of Allende are provided in the electronic annex.
Electronic Annex

Red/Green glasses are available upon request from the first author (dominik.hezel@uni-koeln.de) - or can be purchased at low cost from resellers on the internet

Movies

movie 1 - Allende raw vs mask: This is a side by side comparison of one stack of raw images with the same stack of the schematic 3D model.

movie 2 - Allende rotation: This is a different sample than the previous. The opaque layer around some chondrules is visible. (VGSTudio Max video)

movie 3 - Allende stereographic: (red/green glasses required) This is the same sample as in movie 1. The video was produces from the schematic 3D model. The matrix was removed, chondrules/CAIs and opaques are visible. The opaques are slightly lighter yellow than the chondrules/CAIs. The opaque-layered chondrules are easily spotted. (VGStudio Max video)

movie 4 - Allende with annotations: This stack of raw data is the same as in movie 1. Annotations highlight the features discussed in the text.

movie 5 - Allende fly through: This video was produces from the schematic 3D model. Matrix and opaques are removed, only chondrules are visible. (VGSTudio Max video)

movie 6 - Mokoia raw data vs masks: This is a side by side comparison of one stack of raw images with the same stack of the schematic 3D model.

movie 7 - Mokoia with annotations: This stack of raw data is the same as in movie 6. Annotations highlight the features discussed in the text.
Figures

Figure A1-A4: (red/green glasses required) Additional stereographic images of Allende. The matrix was removed, chondrules/CAIs and opaques are visible. The opaques are slightly lighter yellow than the chondrules/CAIs. The opaque-layered chondrules are visible. Figure A4 is the same as Fig. 5 in the paper.

For submission only:
Movies are lower-resolution
The entire electronix annex can be downloaded from (251 MB) files.me.com/d.hezel/hxuihv