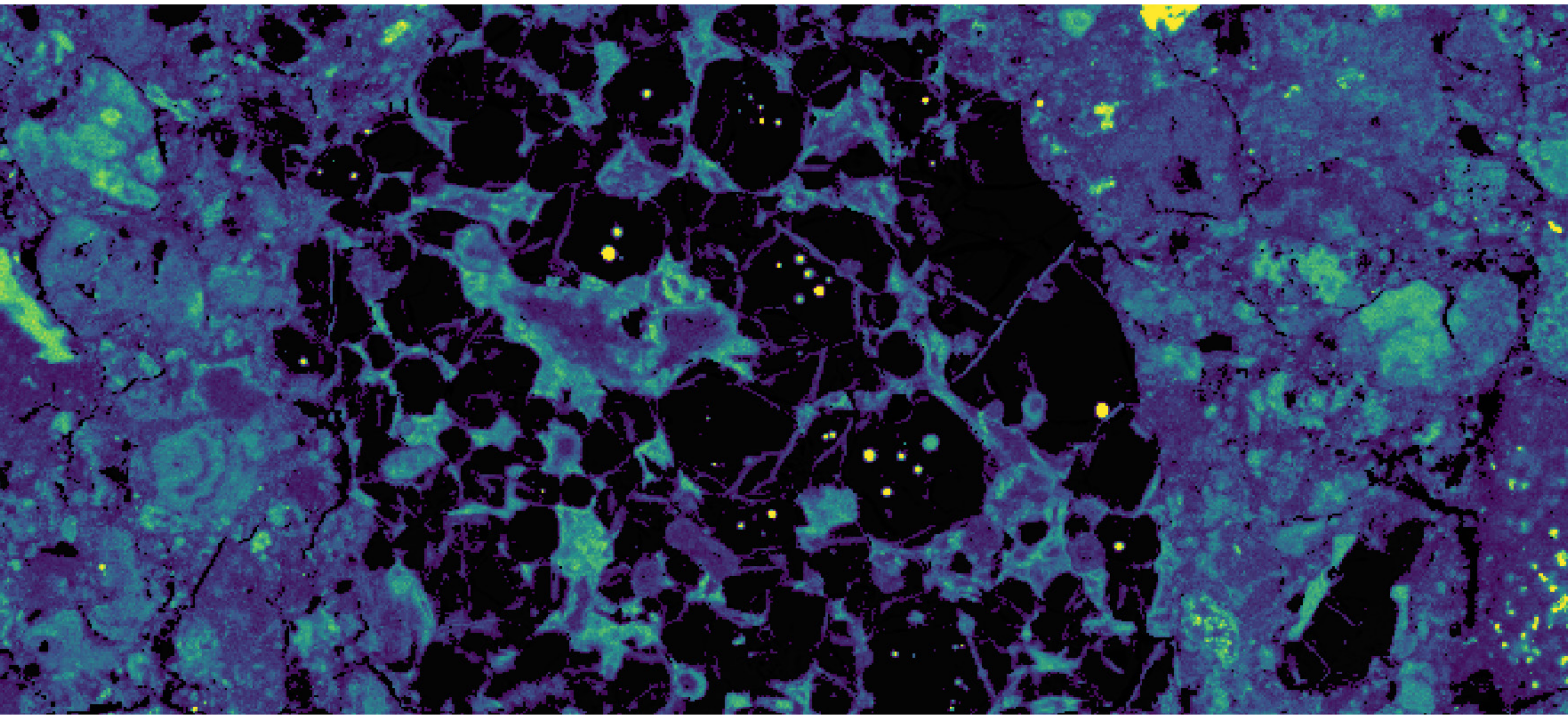
Application Note

The building blocks of our solar system

Studying the Winchcombe meteorite



Seeing beyond

Authors: Dr. Rich Taylor
Carl Zeiss Microscopy, Cambourne, UK
Dr. Martin Suttle
Open University, Milton Keynes, UK

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Introduction

Meteorites are among the most exciting rocks that we can find on Earth because they were formed in outer space and have fallen to our planet's surface by chance. Meteorites are the ancient building blocks of our planets dating back to 4.6 billion years ago and studying them gives us a glimpse into how our solar system formed and evolved.

On the 28th of February 2021 a very special event happened: a meteorite fell from the sky over the UK and fragments of it landed in and around the Gloucestershire village of Winchcombe. Its fiery trail was captured by the national network of cameras that form the UK Fireball Alliance (UKFAll), enabling its final location to be narrowed down with great accuracy. It took less than a day for over 500g of material to be safely collected for the various research teams that would then be involved in studying it. The UKFAll camera network was also able to track the rock back to its point of origin, on the outer edge of the asteroid belt between Mars and Jupiter.

The Winchcombe meteorite is one of the most exceptional meteorites to be studied due to how fast it was able to be collected. Its limited exposure to Earth's atmospheric conditions makes it one of the most spectacularly preserved extra-terrestrial samples, comparable to the sample return missions that collect rocks using satellites from outer space itself. Its pristine nature means everything from organic material to magnetic properties can be analyzed to understand how planets are formed.

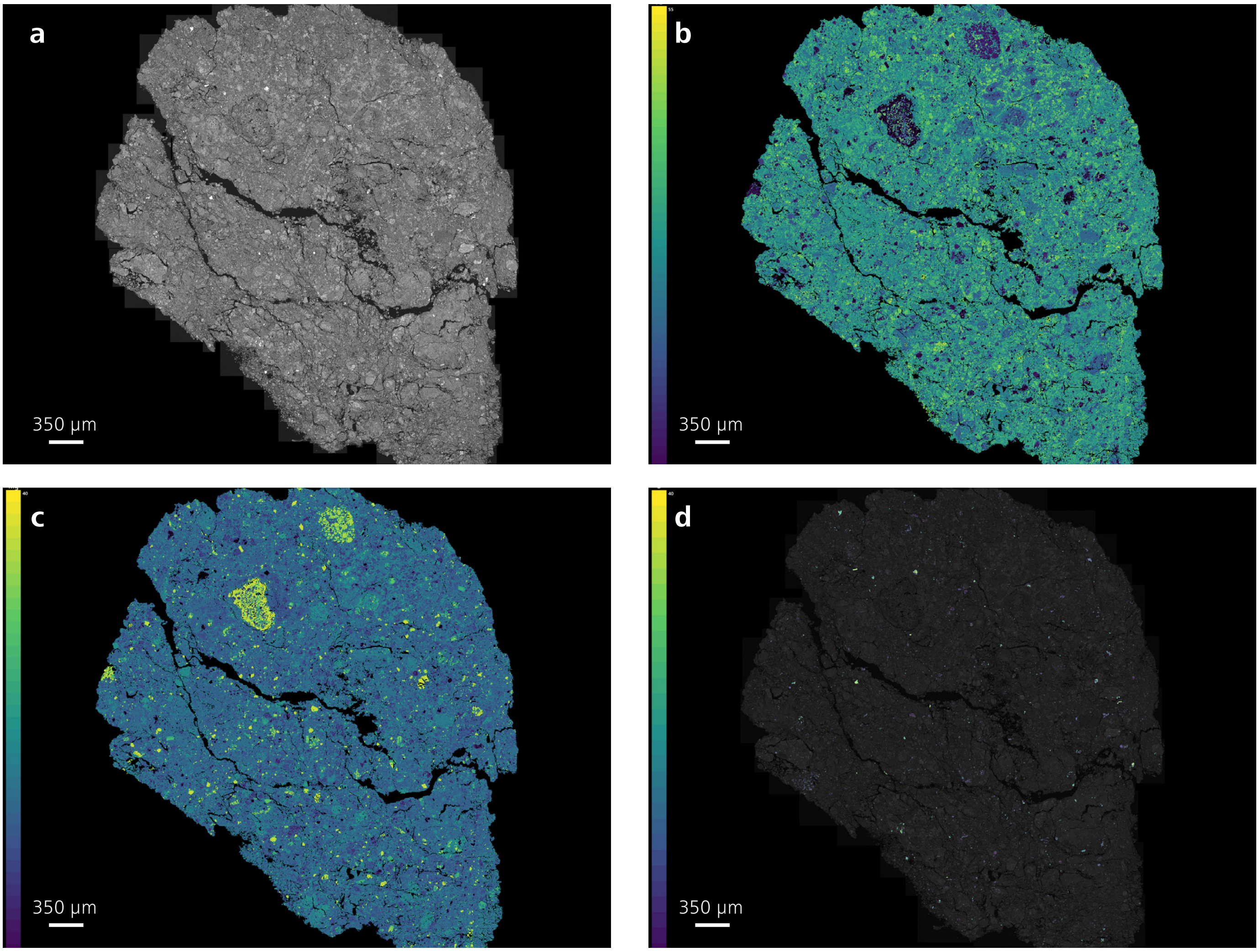

Figure 1 *a) SEM BSE image shows the complex, predominantly fine-grained sample of the Winchcombe meteorite; b-d) quantitative EDS maps of Fe, Mg and S (overlaid on BSE) allow instant visualization of difficult mineralogy even in complex samples. Even with no previous mineral library, all variations can be taken into account for further assessment, e.g. with automated mineralogy.*

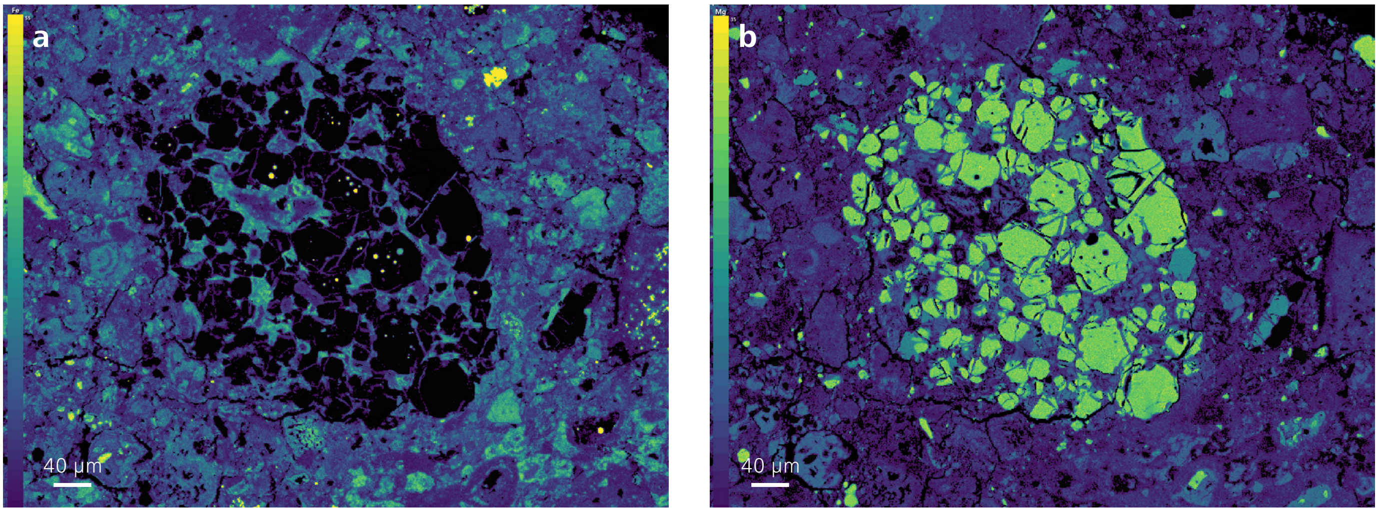

Figure 2 *a-b) Close-up quantitative EDS maps (Fe and Mg) of an olivine aggregate chondrule seen within the sample in Figure 1. Pure Fe-metal inclusions can be seen within the most pristine parts of the forsteritic olivine.*

ZEISS is fortunate to be involved with two of the Winchcombe science teams tasked with understanding the fundamental structure and mineralogy of this fantastic rock. For this research, the ZEISS Mineralogic software suite was used to perform quantitative energy dispersive spectroscopy (EDS) mapping in conjunction with automated mineralogy, alongside the latest µCT scanning software processing techniques. By understanding the Winchcombe sample in both 2D and 3D with complementary approaches, we can gain the greatest insight into the history of this complex sample.

The sample consists of a single fragment mounted in a 25 mm diameter epoxy disk with a polished surface of approximately 4x5 mm. 2D analysis of the polished surface was performed using a ZEISS Sigma 300 field emission scanning electron microscope (FE-SEM) equipped with two Oxford Instruments Ultimax 65 mm^2 EDS detectors for chemical analysis. 3D data were collected with a ZEISS Context µCT system using a standard source and detector setup, combined with deep learning image enhancement and quantitative analysis.

Using combined structural and chemical analysis, the Winchcombe sample has been classified as a rare CM2 carbonaceous chondrite. It can be described as a monomict breccia, meaning that it is composed of a single original rock type, but that rock has been blasted apart by collisions in space and larger fragments are then stuck back together by fine-grained material (clasts within a matrix). The sample has also been altered by fluids that formed part of the rock mass itself, changing the structure and composition of many of the original minerals. The result is a very complex sample that requires many techniques to understand its history.

FE-SEM EDS analysis

Quantitative EDS mapping of the surface of the entire ~15 mm^2 sample allows instant insight into the variation that can be seen within the sample. Comparing the greyscale backscattered electron (BSE) image (Figure 1a) with quantitative element heatmaps (Figure 1b-d) makes it possible to instantly determine the numbers of different materials that make up the broad mineralogy of the sample. Features are visible across multiple orders of magnitude from the silicate chondrules that remain unaltered and up to 500 µm in size (Figure 2a-b), down to submicron clay-like minerals formed from fluid alteration.

Context µCT analysis

Carbonaceous chondrites provide many challenges for traditional µCT imaging. The main goal of the project was to assess the nature of the clasts within the breccia in terms of size, shape, and preferred orientation, along with the clast-to-matrix ratio. These data inform planetary scientists about the processes that occurred on the asteroid body from which the meteorite originated. As the matrix itself is formed from the same material as the clasts, with only a minor density difference, standard µCT imaging makes it difficult to discern the differences.

However, the latest developments in contrast-to-noise image enhancement using the deep learning technology of ZEISS DeepRecon Pro allows these subtle density variations to be used for image analysis and segmentation. A total of 44 clasts were able to be clearly identified within the matrix (Figure 3a-b). The lack of deformation of the clasts themselves, or fabric within the sample, enabled an assessment of the processes happening on the original asteroid body within our solar system.

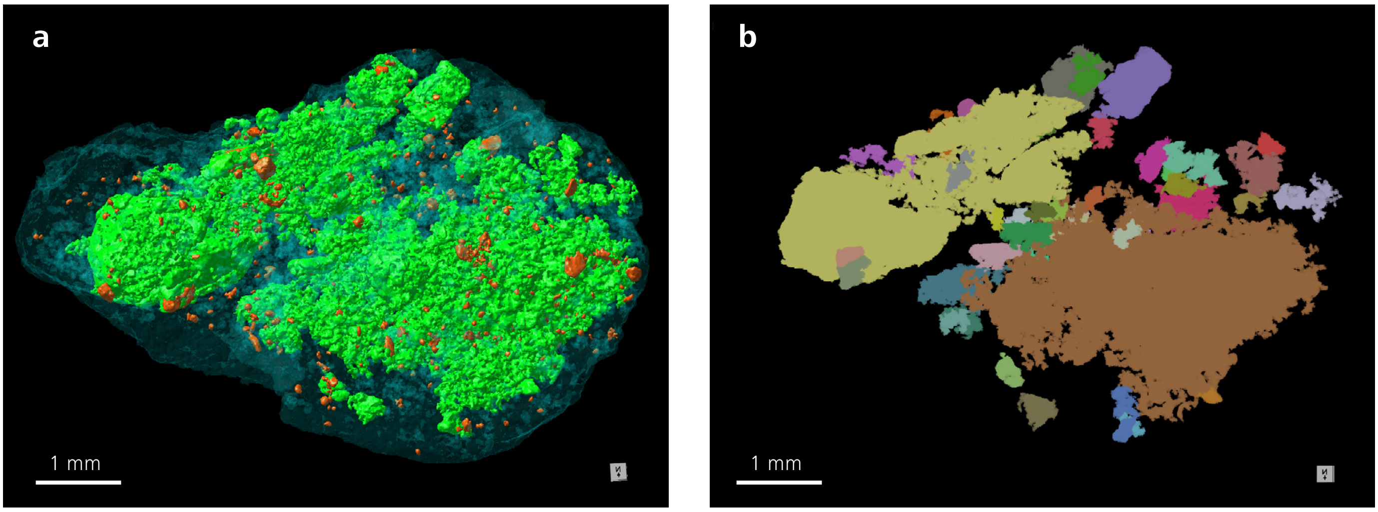

Figure 3 *a) Segmentation following deep learning-assisted reconstruction allowed clasts (green) and matrix (pale blue) to be separated. Sulfide and oxide minerals (orange-red) were also characterized using 3D automated mineralogy with ZEISS Mineralogic 3D. b) Size, distribution, and shape analysis of clasts give insights into collisional processes happening on the initial parental body from which the Winchcombe meteorite originated.*

Image enhancement, reconstruction, and segmentation using the DeepRecon Pro part of the ZEISS Advanced Reconstruction Toolbox and ZEISS Mineralogic 3D mean this complex sample can be analyzed for all the clast information the science team set out to generate. The quantitative approach of Mineralogic 3D also means that the same consistent values for matrix and clast can be applied to multiple fragments of the sample, and subsequently used to compare with other meteorite samples.

Summary

Obtaining quantitative data across multiple microscopy techniques is the best way to generate the information that most accurately describes our sample. The use of quantitative EDS means that complex samples can be interrogated for bulk and mineral compositions straight from SEM, streamlining the process of generating new mineral libraries for automated mineralogy. By using the new quantitative approach for lab-based µCT, the maximum amount of information can be gained from precious meteorites and space mission samples before any destructive techniques are used.

Carl Zeiss Microscopy GmbH
07745 Jena, Germany
microscopy@zeiss.com
www.zeiss.com/microscopy