SUPPLEMENTAL MATERIALS

to the manuscript "Petrogenesis of Miller Range 07273, a new type of anomalous melt breccia: Implications for impact effects on the H chondrite asteroid", authors Alex M. Ruzicka, Melinda Hutson, Jon M. Friedrich, Mark L. Rivers, Michael K. Weisberg, Denton S. Ebel, Karen Ziegler Douglas Rumble III, Alyssa A. Dolan

Contents

Details on analytical methods

Optical microscopy (OM)

We used optical microscopy methods for the petrographic examination of a thin section of MIL (MIL 07273,12). We determined misorientation angles for olivine grains ($\geq$ 50 µm), using angles defined by Stöffler et al. (1991), Schmitt and Stöffler (1995), and Schmitt (2000), and summarized by Ruzicka and Jamsja (2010) to rigorously identify undulatory, weak mosaic, and strong mosaic extinction for each grain. Extinction angles and other data (presence or absence of fractures, planar deformation features, recrystallization textures) was used to assign each grain to one of six shock stages defined by Stöffler et al. (1991). The data were used to determine both a conventional shock stage (the highest category shown by at least 25% of the

grains as defined by Stöffler et al., 1991) and a "weighted shock stage" (the mean of all grain shock stages, as defined by Jamsja and Ruzicka, 2010 and Ruzicka et al., 2015).

Electron Microprobe Analysis (EMPA)

A Cameca SX100 at the American Museum of Natural History was used to obtain X-ray maps and quantitative mineral compositions. The maps combine wavelength dispersive spectral (WDS) and energy dispersive spectral (EDS) data generated from 1-µm-diameter beam spots spaced 5 µm apart using a moving stage and stationary electron beam ("stage maps"). Operating conditions were 15 kV accelerating voltage, 20 nA sample current, and a dwell time of 20 ms. Quantitative mineral compositions were determined on nominally 1-µm-diameter spots with WDS using natural and synthetic standards, counting times of 20 s on peak and 10 s on background (off-peak) spectrometer positions, and other operating conditions the same as for the maps. Relative uncertainties (2σ), based on counting statistics, for major elements (Si, Fe, Mg) are calculated to be <2% and for Ti, Cr, Mn and Ca they are 10%, 10%, 9% and 5%, respectively. Data reductions were carried out using methods described by Pouchou and Pichoir (1991).

Scanning Electron Microscopy (SEM)

A Zeiss Sigma Variable Pressure-Field Emission-Scanning Electron Microscope (VP-FEG-SEM) with an attached high-efficiency XMax50 silicon-drift energy dispersive spectrometer and AZtec 3.1 and 3.2 Oxford Instruments Nanoanalysis software at Portland State University was used to study MIL using backscattered electron (BSE) imagery, X-ray mapping, and X-ray line scans. For this work the SEM was operated at 15 keV accelerating voltage and

beam currents were of order ~5 nA. A BSE montage of the entire section was obtained as well as BSE images of selected targets. In addition, twenty-four fields at various magnifications covering a total area of ~2 mm^2 were mapped by EDS (1024 x 768 pixels) and BSE (2048 x 1646 pixels) using a fixed stage and moving electron beam ("beam maps"), with each field having an EDS counting duration of 15.7 min real time and 7.87 min (472 sec) live time, and 84-87 million total X-ray counts. Nine traverses (line scans) were obtained for metal grains, with each traverse ~140-280 µm long and having 1500 step intervals (i.e., analysis steps every ~0.09-0.19 µm), EDS live time counts between 4.37-5.75 min (262-345 sec), and 46-61 million total X-ray counts. Quantitative phase chemical data were obtained from maps and traverses by converting count rate data to concentrations using energy and beam calibration on a pure Cu standard and factory quantitative standardizations for elements of interest. In EDS maps, analyses were obtained in user-defined extract areas, typically so as to maximize areas (total counts) while still avoiding overlap effects with cracks or adjacent phases; these areas were typically on the order of tens of µm^2 but down to ~1 µm^2 for some matrix grains. Although included in the spectra, oxygen was calculated by stoichiometry for all phases except metals and sulfide. Analyses were accepted if totals ranged between 97-102 wt% and if mineral stoichiometry was acceptable: 3.00 ± 0.02 cations/4O for olivine (2.71-2.96 cations/4O for difficult-to-analyze tiny matrix olivine), 2.00 ± 0.02 cations/3O for pyroxene (1.96-2.04 cations/3O for difficult-to-analyze tiny matrix pyroxene), 5.00 ± 0.05 cations/8O for feldspar, 3.00 ± 0.05 cations/4O for chromite, and ~5 cations/8O for phosphate. To further ensure that analyses of olivine, low-Ca pyroxene, and chromite excluded contaminating sulfide or metal that could artificially raise Fe contents, only those analyses with S and Ni below the detection limit were accepted for these phases in non-matrix areas. Many analyses have low S and Ni and these

low values likely represent the true composition of the phases. In reporting averaged concentration data for phases, upper limits are shown for elements that have both many zero values (below detection) and non-zero values (above detection) in different analyses of the same phase. In these cases, upper limits were estimated as the averages of non-zero values.

Modal Analysis

Metal and sulfide abundances were estimated from different image data types, including the microprobe chemical map, a reflected light optical mosaic, and a BSE image mosaic. Data were analyzed using ImageJ and the Color Inspector 3D plug in, to group pixels into 10-35 color bins, assigning these colors to various phases, and summing the pixels for these phases to determine areal fractions.

Geothermometry

Pyroxene analyses were used for geothermometry using the method of Lindsley and coworkers (Lindsley and Anderson, 1983; Lindsley, 1983) including a digitized version of their pyroxene graphical geothermometer. A temperature was assigned to each analysis by interpolation between 100 ℃ contours, with an approximate precision of ±10 ℃. A contour for 1300 ℃ representing a metastable condition was assumed, making high-temperature values (>1200 ℃) approximate.

Synchrotron X-ray Microtomography and Digital Data Analysis

Various samples were studied with synchrotron x-ray computed microtomography (μCT) apparatus on beamline 13-BMD at the GSE-CARS sector of the Advanced Photon Source, with

parameters optimized for the imaging of chondrites (Ebel and Rivers, 2007). Imaging data was collected with monochromatic x-rays and at resolutions found in Table SM-1 in this Supplement. Resolutions were selected to optimize the results for various µCT-based investigations. Several larger (200-400 mg, Table SM-1) samples were imaged with appropriate conditions to obtain representative 3D-based opaque (metal, sulfide) mineral volume abundances (Friedrich et al., 2008). Higher resolution imaging on smaller chips was performed to quantify the porosity in the samples with methods used in Friedrich et al. (2008) and Friedrich et al. (2014). Porosity errors were derived from those found by Friedrich et al. (2013) using the same methods. Bulk density and the collective orientation of metal grains in the samples, the latter being used to examine the degree of compaction of the samples (Friedrich et al. 2008b, Friedrich et al., 2014), were obtained for all samples regardless of the resolution data were collected.

Electron Back Scatter Diffraction (EBSD)

An EBSD system integrated with the SEM at Portland State University was used to study the crystallography of section MIL 07273,12. EBSD sample preparation of this section included hand polishing with colloidal silica solution for 20 minutes, about half the time desired, which was cut short by peeling of the epoxy surrounding the sample. A thin coat (5.1 nm thickness) of evaporated C was subsequently applied. EBSD equipment included a NordlysNano EBSD detector with a high-end digital CCD camera and 4-diode forward scattered electron detectors; EBSD data were obtained and processed using integrated AZtecHKL and Channel5 software. Criteria for grains were set at a minimum of five contiguous pixels, and a maximum boundary misorientation (critical misorientation) of 15°. Crystal match files in HKL, American Mineralogist, and ICSD databases in AZtec software were supplemented with other data from

the literature. For EBSD work, the SEM was operated at 20 keV, and EDS maps were obtained concurrently with electron backscatter diffraction pattern (EBSP, or Kikuchi-pattern) data. Acquisitions included 4 x 4 binning of EBSPs with noise reduction obtained by summing either four or five EBSP frames. Both survey and larger maps at different step intervals and sizes were obtained. Table SM-2 in this Supplement gives mapping parameters for the six largest data sets obtained.

Elemental Analysis

The method outlined in Friedrich et al. (2003) and expanded by Wolf et al. (2012) was used to quantify 51 trace, minor, and major elements by Inductively Coupled Plasma Mass Spectrometry (ICPMS). Sample aliquots of ~100 mg were ground in a clean agate mortar and pestle and dissolved using a combination of HF and HNO_3 in a microwave digestion system. The resulting solution was taken to near dryness in Teflon beakers in a specially-constructed dry bath incubator at 75°C. $HClO_4$ was then added and again the solution was taken to incipient dryness. The samples were then taken up in a ~2% HNO_3 solution after adding internal standards (Be, Rh, In, Tl). During ICPMS analysis, the Allende Standard Reference Meteorite (Jarosewich et al., 1987) was used for external calibration and quantification of the elemental analytes. Eight replicates of samples (JSC subsample designations MIL 07273,6 and MIL 07273,10) were analyzed. Sample sizes in mg were 104.8, 109.0, 98.7, 98.0, 93.3, 68.0, 118.7, 102.4.

Oxygen Isotopic Analysis

Oxygen isotopic analyses were performed on five small (2-4 mg-sized) chips of MIL 07273 from two portions of the rock. Two of the MIL 07273 samples (each from subsample MIL

07273,6) were analyzed for oxygen isotopes using laser fluorination of acid-washed samples (to remove terrestrial weathering products) at the Geophysical Laboratory of the Carnegie Institution during the same analytical experiments as those completed for the work of Troiano et al. (2011). A detailed explanation of the techniques used can be found there. Another suite of sample chips (from subsample MIL 07273,10) were analyzed for oxygen isotopes at the University of New Mexico Institute of Meteoritics by laser fluorination on acid-washed samples, following the procedures outlined by Agee et al. (2013).

Table S1. μCT parameters, sample details, and digitally extracted data.

sample origin	mass (mg)	resolution	energy	meteorite volume (mm^3)	porosity* (%)	metal (vol %)	sulfide (vol %)	metal +sulfide (vol%)	density (g/cm^3)	metal preferred orientation (C)
MIL 07273,6	423.11	12.24 μm	46.0 keV	120.7	n.d.	7.0	0.95	8.0	3.51	0.281
MIL 07273,10	489.97	7.72 μm	46.6 keV	139.1	n.d.	6.7	1.06	7.8	3.52	0.188
MIL 07273,10	283.31	7.72 μm	46.6 keV	77.4	n.d.	9.3	1.48	10.8	3.66	0.293
MIL 07273,10	225.66	7.72 μm	46.6 keV	67.4	0.5	5.4	1.08	6.5	3.35	0.266
MIL 07273,10	134.28	4.97 μm	43.7 keV	37.4	n.d.	6.6	0.99	7.6	3.59	0.205
MIL 07273,10	20.29	2.78 μm	39.0 keV	5.6	0.7	9.8	1.80	11.6	3.65	0.278
MIL 07273,10	50.81	2.78 μm	39.0 keV	14.7	n.d.	8.2	2.22	10.4	3.45	0.371

* n.d. = not determined

Table S2. EBSD mapping parameters for the six largest maps of MIL 07273,12.

Map	Target	Step interval (µm)	Map size (pixels)	EBSD camera exposure time (ms/pixel)	Number of exposure frames	Acquisition time (hr:min)	EBSPs saved?	Hit rate (%)*
Site 273 #1	Matrix, small clasts	0.15	367 x 274	21.3	4	2:46	Yes	99.4
Site 273 #2	Matrix, small clasts	0.2	672 x 505	18.4	5	11:43	No	97.6
Site 257	Matrix, large clasts	0.52	650 x 483	21.0	5	10:46	Yes	98.3
Site 226	Coarse silicates (bent olivine bars)	1.0	462 x 363	18.4	5	6:03	No	94.9
Site 232	Coarse silicates (pyroxene chondrules)	0.42	647 x 481	21.0	5	10:41	Yes	96.3
Site 251	Coarse metal	0.65	479 x 360	18.4	5	6:01	No	96.3

*Number of pixels with solutions in the original acquired maps.

Table S3. EBSD data for larger (>5 µm diameter) olivine grains in five map sites*.

Site	Grain diameter (µm)	Grain area (µm^2)	Average GOS	Types of grains
273 #2	5-20	1245	5.0 ± 1.8	Small clasts in matrix, partly recrystallized
226	5-60	54552	3.8 ± 2.2	Large clasts, chondrule with bent bars
251	5-26	3071	4.0 ± 1.8	Large clasts
257	5-115	21316	4.8 ± 2.6	Large and small clasts
232	5-22	2462	5.5 ± 2.9	Large clasts
Average			4.6 ± 0.7	
Average by area			4.1 ± 2.3	

Table S4. Inferences for high-temperature (T = temperature) timescales and cooling rates based on chemical variations in metal grains in MIL 07273, assuming low pressure conditions.

Constraints	Assumption	Inference
Ni-rich halos around taenite; theoretical diffusion coefficients of Fe and Ni in liquid metal[1]	Halos produced by diffusion in liquid metal over characteristic length scale of 15 µm	≤56 ms timescale at ~1500 °C; timescale could be shorter if halos created in part by dissolution
Ni-rich halos around taenite; experimental diffusion coefficients in metal[2]	Cooling has to be sufficiently rapid in solid metal to avoid diffusion over 15 µm length scale	≥300 °C/hr at T ≥ 1300 °C; cooling could be much faster if halos established in liquid metal
Narrow (1-5 µm) Ni-rich rims on martensitic metal grains; experimental diffusion coefficients in metal[2]	Cooling has to be sufficiently rapid in solid metal to avoid diffusion over 3 µm length scale	≥1-2 °C/s at T ≥ 1300 °C; cooling could be faster if rims created by solidification zoning

[1] Protopapas et al. (1973)

[2] Heyward and Goldstein (1973); Million et al. (1981).

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