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Research paper

Insights into chondrule formation process and shock-thermal history of the Dergaon chondrite (H4-5)

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ABSTRACT

The Dergaon fall represents a shock-melted H4-5 (S_5) ordinary chondrite which includes at least ten textural varieties of chondrules and belongs to the high chondrule-matrix ratio type. Our study reveals that the chondrules are of diverse mineralogy with variable olivine-pyroxene ratios (Type II), igneous melt textures developed under variable cooling rates and formed through melt fractionations from two different melt reservoirs. Based on the experimental analogues, mineralogical associations and phase compositions, it is suggested that the Dergaon chondrules reflect two contrasting environments: a hot, dust-enriched and highly oxidized nebular environment through melting, without significant evaporation, and an arrested reducing environment concomitant with major evaporation loss of alkali and highly volatile trace elements. Coexistence of chlorapatite and merrillite suggests formation of the Dergaon matrix in an acidic accretionary environment. Textural integration and chemical homogenization occurred at $\sim$1 atmospheric pressure and a mean temperature of 765 °C mark the radiogenic thermal event. Equilibrated shock features (olivine mosaicism, diaplectic plagioclase, polycrystalline troilite) due to an impact-induced thermal event reflect a shock pressure >45 GPa and temperature of 600 °C. By contrast, the local disequilibrium shock features (silicate melt veins comprising of olivine crystallites, troilite melt veins and metal droplets) correspond to a shock pressure up to 75 GPa and temperature >950 °C.

1. Introduction

The Dergaon chondrite shower is one of the spectacular meteorite falls in Assam, Northeast India on 2nd March, 2001 at 16:40 (Shukla et al., 2005). The samples investigated in this study are part of a thin fusion crust bearing 0.8 kg fragment recovered immediately after the fall from a village north of Dergaon and south of Majuli island (96°46′48″E, 26°46′32″N). An earlier study, mostly focussed on integrated petrology, bulk chemistry, oxygen isotopes, noble gas, and cosmic ray track density assigned Dergaon as an H5 ($S_{2\text{-}3}$) ordinary chondrite (Shukla et al., 2005). However the anomalous low K content ($\sim$340 ppm) in Dergaon as compared to the mean K content of 786 ppm for H chondrites (Kallemeyn et al., 1989) remains unexplained. Further, a detailed inventory of various chondrules in the Dergaon chondrite was not adequately highlighted in the light of their formation history. These points prompted us to examine in detail the microtextures and their shock induced metamorphism from another meteoritic fragment of Dergaon chondrite. Subtle changes of mineral chemistry during thermal and shock metamorphism were duly considered during interpretation of chondrule formation and shock-thermal history of the Dergaon chondrite.

2. Analytical techniques

Petrographic observations were carried out using a Zeiss Polarising Microscope. Mineral compositions were determined using a Cameca SX 100 electron microprobe with three wavelength dispersive spectrometers at the Physical Research Laboratory, India. Counting times for the elements were kept generally 10–20 s except for Na, which was 7 s to reduce the volatilization effect. Operating conditions were 15 kV accelerating voltage, sample

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current 15 nA and 1 μm beam diameter. Natural mineral and metal standards were used and the data were corrected for absorption, fluorescence and atomic number effects. Synthetic glass NIST 610 was run during certain intervals to check drift of the instrument. The 2σ error of most elements is better than ±5%. Estimation of modal mineralogy, chondrule-matrix ratio and relative abundance of silicates, metal and sulphides was conducted from four polished thin sections with the aid of manually operated routine point count device under optical microscope, mosaic of Back Scattered Electron (BSE) images and automated EPMA at 1 μm spacing, the latter employed for the recrystallized matrix.

3. Petrography and mineral compositions

The petrographic study was carried out on a dull, grayish brown, semi-oval fragment (6 cm × 4.5 cm × 2 cm), covered with cherry brown, close textured fusion crust and its interior shows distinct chondrules in brownish recrystallized matrix (Fig. 1). The Dergaon chondrite appears as a close-packed aggregate of a large variety of chondrules, a few chondrule clasts and compound chondrules set in a semi-transparent to translucent finely recrystallized silicate matrix enriched with metal-troilite. The chondrule population includes readily delineable (47 vol.%), poorly defined (38 vol.%) and well delineated (15 vol.%) types. Porphyritic olivine (PO) and cryptocystalline (C) chondrules are considerably larger in contrast to small glassy (G) droplet chondrules. Radial pyroxene (RP) chondrule clasts are most common and relatively larger in size, whereas clasts of barred olivine (BO) and barred pyroxene (BP) chondrules are rare.

Mineralogically the sample contains ~35% olivine, ~30% orthopyroxene, 8% feldspar, 8% translucent to cryptocrystalline glass, 5% clinopyroxene, 8% metal, 4% troilite and 2% accessories like chromites, merrillite and chlorapatite. Chondrule-matrix ratio varies from 60:40 to 80:20 in different regions of the thin section. Average mineral compositions are provided in Table 1. Detailed analyses are provided in online supplement (Supplementary Tables 1–19).

3.1. Chondrules

The Dergaon chondrite contains nearly 75% porphyritic (PO, PP, POP, BO, BP) and ~25% non-porphyritic chondrules (RP, C, G and GP), besides sibling and independent types of compound chondrules (cf. Wasson et al., 1995).

Figure 1. Hand specimen photograph of the Dergaon chondrite. Note the development of a thin fusion crust.

Table 1
Mineral phase compositions (mean and range given) of Dergaon chondrite.

Minerals	No. of analyses	Range	Mean (S.D.)
Olivine	96		
Fa (mole%)		18.73–21.43	20.28 (0.56)
Orthopyroxene	73		
Fs (mole%)		16.72–22.46	17.96 (0.72)
Clinopyroxene	24		
En-Fs-Wo (mole%)		$En_{36-59.6}Fs_{2.97-11.98}Wo_{37.24-58.26}$	$En_{46.63}Fs_{6.74}Wo_{47.32}$
Plagioclase	10		
An (mole%)		11.85–14.8	13.26
Glass	52		
An-Ab-Or (mole%)		10.31–75.3	29.83
Merrillite			$Ca_{8.04}Na_{0.86}Fe_{0.11}Mg_{0.81}P_{6.2}O_{24}$
Chlorapatite			$Ca_{13.8}Na_{0.2}P_{4.3}O_{25}$
Chromite			
$Cr^{\#}$: Cr/(Cr + Al)		0.83–0.85	$Cr^{\#}$: 0.84
$Fe^{\#}$: Fe/(Fe + Mg)		0.72–0.72	$Fe^{\#}$: 0.72
Kamacite	21		
Ni (wt.%)		3.32–7.02	6.15
Taenite	10		
Ni (wt.%)		7.6–20.46	11.64
Troilite			
S (wt.%)		35.78–36.50	36.27

S.D.: Standard deviation.

The Dergaon porphyritic olivine (PO) chondrules are variable in size from 3.25 mm × 1.25 mm to 145 μm across with readily delineable outline. Coarser, euhedral to subhedral olivine grains (Fa: 19.2–20.9) are embedded in a translucent feldspathic glassy mesostasis ($An_{13.06-37.78}Ab_{59.75-79.07}Or_{2.42-3.43}$). However, mesostasis of some PO chondrules is heterogeneous and yields compositions similar to Ca-rich pyroxene ($En_{46.6}Fs_{7.2}Wo_{46.2}$), albitic feldspar ($An_{13.1}Ab_{79.1}Or_{3.4}$) and their mixed varieties. High-Ca pyroxene ($En_{45.3}Fs_{7.9}Wo_{46.8}$) is also present as a microcrystalline phase within the chondrule. Mesostasis to phenocryst ratios in these chondrules vary between 50 and 90. Metal-troilite in chondrule occupies maximum up to 10 vol.%. One of these PO comprises closely packed aggregates of subrounded to rounded olivine grains with glass-rich and glass-poor mesostasis (Fig. 2b, Supplementary Table 1).

The porphyritic pyroxene (PP) chondrules (Fig. 2c,d) with a high phenocryst/matrix ratio are relatively less in abundance and their sizes vary up to 1.3 mm × 1.0 mm. Phenocryst of prismatic low-Ca pyroxene ($Fs_{16.9-17.4}Wo_{0.8-0.9}$) in albitic mesostasis ($An_{12.7-35.4}Ab_{62.1-85.1}Or_{2.3-2.5}$) is the most common feature (Supplementary Table 2).

The porphyritic olivine pyroxene (POP) chondrules (av. size 0.36 mm) are widely distributed with a poorly defined outline (Fig. 3a). These contain granular and fractured olivines (mean $Fa_{20.1}$), prismatic pyroxenes (mean $Fs_{17.7}$) up to 1.3 mm × 1.0 mm and rarely high-Ca pyroxenes within a uniform translucent glassy matrix of mean composition $An_{23.8}Ab_{72.5}Or_{3.7}$ (Supplementary Table 3).

The barred olivine (BO) chondrules are relatively rare and generally found as clasts (Fig. 3b). Besides parallel olivine bars, diversely oriented bars are also noticed in two chondrules (diam. 400 and 465 μm) and one of these shows a 35 μm thick olivine rim from which crystals grew inward (Fig. 3c). Olivine bars, irrespective of their orientations and widths, are nearly homogeneous both within the chondrule and between the chondrules ($Fa_{19.85-20.72}$). Clear transparent to microcrystalline, translucent albitic glass ($An_{11.9-21.5}Ab_{77.4-85.6}Or_{1.1-2.5}$) occasionally with needle-like pyroxene crystallites constitute the mesostasis (Supplementary Table 4).

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