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# Studies and characterizations of the Al Zarnkh meteorite

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**Abstract–**A newly fallen Sudanese meteorite named Al Zarnkh was investigated using room and liquid nitrogen temperature Mössbauer measurements, X-ray diffraction (XRD), and electron probe microanalysis (EPMA) in conjunction with energy dispersive X-ray microscopy. The Mössbauer spectra exhibited strong paramagnetic doublets with magnetic sextets. The doublets are assigned to olivine and pyroxene, while the magnetic sextets are assigned to troilite and kamacite. Based on microprobe analyses and textural studies, olivine is the most abundant phase and occurs as fine to medium grained laths both in the groundmass and in barred olivine chondrules. Both orthopyroxenes and clinopyroxenes are present and these tend to be granular. Plagioclase is an abundant interstitial groundmass phase. Chromites were detected in some groundmass olivine and are highly chromium- and iron-rich with no $Fe^{3+}$ detected. The kamacite contains small amounts of Co. The mole fraction of the Fe end-member of olivine (fayalite) and orthopyroxene (ferrosilite) are found to be about 28% and 23%, respectively. These values are compared with that obtained from two chondritic meteorites. Based on these results, the studied meteorite is classified as an ordinary LL5 chondrite.

## INTRODUCTION

Stony meteorites are divided into chondrites, which generally contain mm-sized spheroidal objects called chondrules, and the achondrites, which include meteorites that lack chondrules and are chemically dissimilar to chondrules (Knudsen 1989). These differences are thought to arise because the parent bodies were produced in different regions of the solar nebula. Their slightly different chemical and structural properties resulted from different amounts of thermal processing and the uneven distribution of their constituent materials. The chondrites are divided into three categories: carbonaceous, enstatite, and ordinary chondrites. The ordinary chondrites are further subdivided into three groups, the H, L, and LL types. The differences between these depend mainly on the weight percentages of the total iron and its distribution between the metal and silicate phases. The H group (high total Fe) contains a weight percentage of 25 to 28% total Fe, and the mol% of fayalite (Fa), the end-member of the olivine group, is in the range 16–20%. The L-group chondrites have a total Fe content of about 20 to 25% and the mol% of Fa range goes to 22–26. The LL-group have low total Fe and low metal in general i.e., 19 to 22% total Fe and a range of about 27–31 mol% of Fa (Dodd 1981). From the above it can be seen that the total metal content is to some extent inversely related to the modal abundance of olivine and to its FeO content.

In our previous studies, three meteorites have been investigated. Two of them were classified as ordinary chondrites and one as an achondrite (Gismelseed et al. 1994; Abdu et al. 1997). In this study, a newly fallen meteorite named Al Zarnkh will be investigated. The details of the fall were reported in *The Meteoritical Bulletin No. 88.* To better understand the crystal chemistry, mineralogy, and oxidation state of the iron-bearing phases in this meteorite, we report on our detailed investigation using Mössbauer spectroscopy together with X-ray diffraction (XRD) and electron probe microanalysis (EPMA).

## EXPERIMENTAL METHODS

The meteorite was found as two pieces weighing 0.7 kg in total. It was found soon after its fall on February 8, 2001 at Al Zarnkh, a village located in the western region of Sudan, about 150 km west of the town of Barah. The specimen was recovered in fresh condition and covered with a characteristic fusion crust less than one millimeter in thickness.

Four polished thin sections were examined using a polarizing microscope. Minerals were analyzed on a Camera Camebax SX50 EP microanalyzer in the Central Science Laboratory of the University of Tasmania, Australia. The operating conditions included a beam current of 25.15 nA and an accelerating voltage of 15.07 kV.

Mössbauer spectra were obtained at 295 K and 78 K on a powdered sample using a constant acceleration Mössbauer spectrometer with 50 mCi $^{57}$Co in Rh source. The low temperature measurement was performed using liquid nitrogen flow cryostat. The spectrometer was calibrated with α-Fe foil spectrum at RT. The measured data were analyzed using a non-linear least-square fitting program assuming Lorentzian lines. The line width and the intensity of the two lines of each quadrupole doublet were constrained to be equal. For the magnetic subspectra, when the magnetic interaction is dominating the electric interaction, the quadrupole interaction is described by the formula:

$$QS = [(v_6 - v_5) - (v_2 - v_1)]/2 \quad (1)$$

where $v_1$, $v_2$, … $v_6$ are the peak positions in the sextet with increasing velocities.

Powder X-ray diffraction (XRD) was performed using a Philips PW1820 diffractometer with the range of 2θ from 10° to 70° and a PDP11 microcomputer for analysis. The sample was prepared for XRD by pressing the powder into the middle of the well of the aluminum sample holder using a glass slide. The multiple pressing was necessary because the top of the sample should be coplanar with the top of the aluminum holder. The phases were identified by performing multiple searches on a database using PW 1876 PC-identify and PW 1877 APD (automatic powder diffraction) software programs.

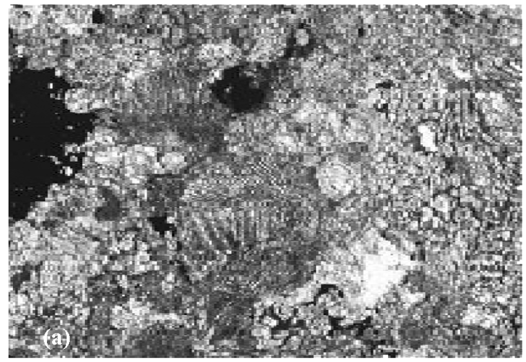
## RESULTS AND DISCUSSION

### XRD

The X-ray powder diffraction analysis indicated that the principal phases in the Al Zarnkh meteorite are olivine, pyroxene, troilite, and kamacite in decreasing order of abundance. The results are in full agreement with those reported in the literature (Abdu et al. 1997).

### Petrography

The examined thin sections showed that the meteorite is chondritic with a granular texture. The groundmass consists of granular clinopyroxene, orthopyroxene, olivine, plagioclase, troilite, kamacite, and chromite. Olivine is the most abundant groundmass phase and occurs as a fine- to medium-grained laths, whereas the pyroxenes tend to be granular. Between the groundmass lath-like olivine are gray areas of oligoclase (Fig. 1a). The groundmass opaque minerals include troilite and kamacite that occur both as granules and irregular, lobate grains (Fig. 1b). Minute melt inclusions were observed within



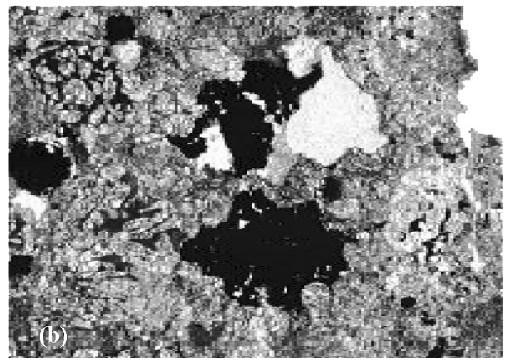


Fig. 1. a) Well-defined chondrules showing herringbone barred olivine. The granular mineral to the left of the picture is pyroxene mixed with prismatic olivine; b) A general view of the groundmass texture. The opaque mineral is kamacite and the colorless areas are holes in the slide. The grey areas at bottom left are oligoclase.

some troilite grains but were too small to analyze. Chromites were also detected in some groundmass olivine, and minute inclusions of what could be metallic iron were observed within some kamacites. These detections were 1–2 μm in size and thus too small to analyze. The groundmass encloses large chondrules up to 4 mm in diameter. They range from those with a distinct outline to recrystallized types that merge imperceptibly into the groundmass. Some are fragmentary. Texturally, there are two types. In plane polarized light, there is a single example of an apparently structureless chondrule consisting of very fine grained olivine (<3–10 μm). However, in cross-polarized light, an extinction pattern radiates away from a single point on the edge of the chondrule, presumably representing radial growth of olivine (Fig. 2a). The second more abundant type consists of distinct olivine-barred chondrules in which olivine laths, often showing a herringbone structure, are interlaminated with oligoclase, granular orthopyroxene, and troilite. One example of this type has a concentric ring of granular troilite at the edge (Fig. 2b).

### Mineral Chemistry

A total of 76 silicate and oxide analyses and 18 opaque analyses were obtained. Representative examples are presented in Table 1. Pyroxenes were normalized to six

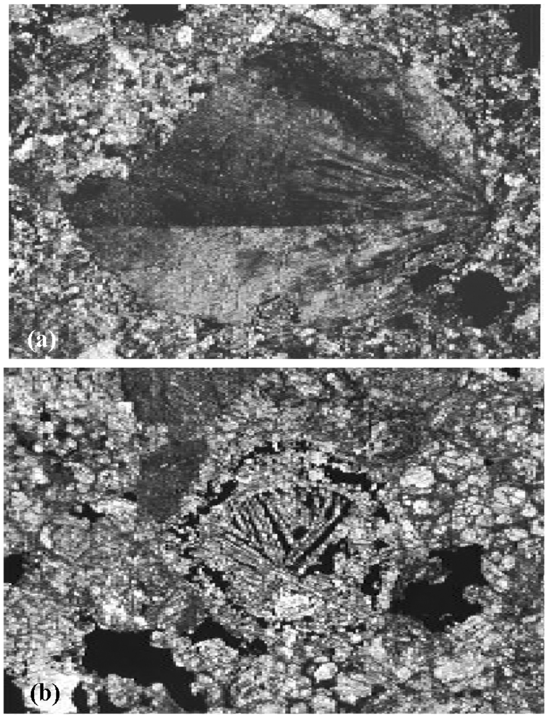



Fig. 2. a) Large truncated chondrule showing radiating prismatic olivine; b) well-defined chondrule showing barred herringbone olivine. The opaque areas within the chondrule are granular troilite. The larger opaques are kamacite.

oxygens, and site occupancies were calculated according to the IMA guidelines (Morimoto 1989). The clinopyroxenes are diopsides ranging $Wo_{48.37}En_{43.58}Fs_{8.05}$–$Wo_{46.24}En_{45.14}Fs_{8.63}$. The orthopyroxenes are hypersthenes ranging $Wo_{1.69}En_{75.41}Fs_{22.90}$–$Wo_{2.49}En_{74.68}Fs_{22.84}$. The plagioclase compositions were normalized to 32 oxygens (Deer et al. 1992). They are oligoclase ranging $Or_{10.25}Ab_{83.64}An_{10.25}$–$Or_{6.33}Ab_{75.52}An_{18.12}$. The olivine compositions were normalized to four oxygens that are highly uniform at ~$Fo_{72}$. The chromites were normalized to four oxygens and are highly chromium- and iron-rich, but normalizing the cations to 3.00 suggests that they contain almost no $Fe^{3+}$. The opaque minerals consist of troilite ($Fe_{49.95}S_{49.90}$) and kamacite of typical 6 wt% Ni and 1.8 wt% Co.

**Mössbauer Measurements**

Figure 3 shows the 295 and 78 K Mössbauer spectra of the Al Zarnkh meteorite. The spectra consist of paramagnetic doublets superimposed on magnetic components. The hyperfine interaction parameters obtained from the fitting of the 295 K spectrum together with XRD results attributed the paramagnetic doublets to the presence of the silicate minerals olivine and pyroxene, while the magnetic components due to the iron sulfide (troilite) and very weak signal of 3% of iron nickel (kamacite) phases. Except for olivine and pyroxene,

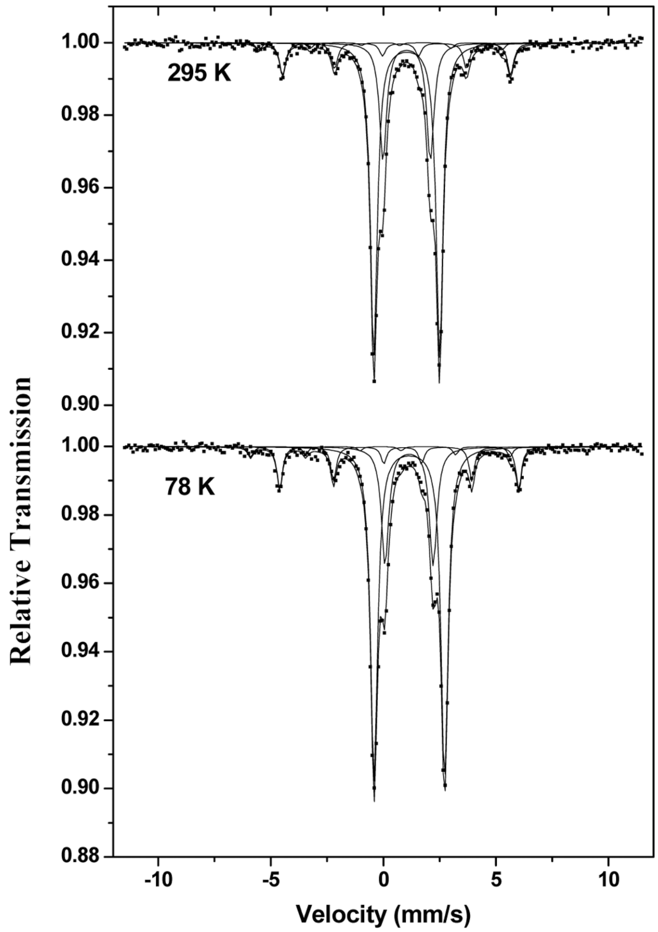



Fig. 3. Mössbauer spectra of the Al Zarnkh meteorite measured at 295 K (above) and 78 K (below).

Mössbauer spectra of paramagnetic phases are sometimes difficult to identify because of their small abundance or overlap with the major peaks. Our detailed EPMA analysis has identified minute inclusions of chromites in some groundmasses olivine, but due to their low concentration we failed to detect them in the Mössbauer spectrum. The liquid nitrogen spectrum shows line profiles similar to those at 295 K in all components and supports the identification of the paramagnetic components. This appears from the temperature independence of the quadrupole splitting of the second doublet ($\Delta E_Q$ = 2.10 mm/s at 295 and 78 K), which is attributed to the $M_2$ site of orthopyroxene in contrast to its $M_1$ site, which is temperature dependent (Bancroft 1973). The Mössbauer parameters are collected in Table 2 and are typical to that published for ordinary chondrites (Paliwal et al. 2000 and references therein). The small relative area of kamacite reduces the amount of total metal phases compared with that in the silicate phases. On the other hand, the olivine showed high relative absorption area on the expenses of the pyroxene contents. Verma and a co-worker (Verma et al. 2002) observed similar trends in their ordinary chondrite Itawa-Bhopii meteorite and inferred that the meteorite underwent severe

Table 1. Selected analysis (in wt%) of the main silicate phases and chromites from the Al Zarnkh meteorite.

| Wt% Oxide | | Olivine | | CPx | | Opx | | Plagioclase | | Chromite | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 37.7 | 37.9 | 37.8 | 53.1 | 53.1 | 54.2 | 54.7 | 65.4 | 65.1 | 0.00 | 0.00 |
| $TiO_2$ | 0.06 | 0.05 | 0.00 | 0.50 | 0.43 | 0.66 | 0.52 | 0.06 | 0.06 | 3.08 | 3.37 |
| $Al_2O_3$ | 0.00 | 0.01 | 0.01 | 0.86 | 0.92 | 0.74 | 0.48 | 21.4 | 21.1 | 5.88 | 5.79 |
| $Fe_2O_3$ | n.d.[a] | n.d. | n.d. | 1.16 | 0.96 | 0.00 | 0.00 | 0.62 | 0.65 | n.d | n.d. |
| $Cr_2O_3$ | 0.06 | 0.04 | 0.04 | 0.69 | 0.75 | 0.43 | 0.24 | n.d. | n.d | 56.6 | 54.0 |
| FeO | 25.0 | 24.9 | 24.9 | 3.83 | 4.29 | 14.5 | 15.0 | n.d. | n.d | 31.6 | 31.6 |
| MnO | 0.41 | 0.52 | 0.45 | 0.26 | 0.26 | 0.50 | 0.45 | n.d. | n.d | 0.67 | 0.58 |
| MgO | 36.5 | 36.9 | 36.7 | 15.5 | 15.8 | 27.4 | 27.3 | n.d. | n.d | 2.13 | 2.09 |
| CaO | 0.03 | 0.01 | 0.03 | 22.7 | 22.1 | 0.91 | 0.97 | 2.77 | 2.45 | n.d | n.d. |
| $Na_2O$ | n.d. | n.d | n.d. | 0.67 | 0.60 | 0.02 | 0.02 | 8.79 | 9.38 | n.d. | n.d |
| $K_2O$ | n.d. | n.d | n.d. | 0.01 | 0.05 | 0.01 | 0.00 | 1.02 | 1.05 | n.d. | n.d |
| BaO | n.d. | n.d | n.d. | n.d. | n.d | n.d. | n.d. | 0.08 | 0.00 | n.d. | n.d |
| Total | 99.8 | 100.3 | 99.9 | 98.1 | 98.2 | 99.4 | 99.6 | 100.2 | 99.7 | 99.9 | 98.2 |

[a]n.d. = not detected.

Table 2. Room temperature and 78 K (between brackets) Mössbauer parameters obtained from the Al Zarnkh meteorite.

| | $\delta^a$ (±0.02) (mm $s^{-1}$) | | $\Delta E_Q{}^b$ (±0.01) (mm $s^{-1}$) | | LW[c] (±0.02) (mm $s^{-1}$) | | B[d](±0.1) (T) | | A (±0.3) (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Olivine | 1.15 | (1.27) | 2.92 | (3.13) | 0.36 | (0.38) | – | – | 60.6 | (60.8) |
| Pyroxene | 1.15 | (1.26) | 2.10 | (2.13) | 0.39 | (0.40) | – | – | 24.0 | (23.7) |
| Troilite | 0.79 | (0.90) | –0.17 | (–0.16) | 0.30 | (0.29) | 31.4 | (33.0) | 12.7 | (12.5) |
| Kamacite | –0.01 | (–0.01) | 0.01 | (–0.01) | 0.33 | (0.29) | 33.6 | (35.8) | 2.7 | (3.0) |

[a]δ = isomer shift.
[b]$\Delta E_Q$ = quadrupole splitting.
[c]LW = line width.
[d]B = magnetic field splitting in Tesla.

oxidation by which the metallic phase ($Fe^0$) is converted to ferrous phase ($Fe^{2+}$) that was incorporated in the silicate olivine matrix. In their systematic studies of Mössbauer absorption areas of 24 ordinary chondrites (Verma et al. 2003), they developed a one-dimensional plot of the olivine/pyroxene in addition to a two-dimensional plot of area of metallic phases versus area of silicate phases. The former chart gives a better zone separation for the three groups, H, L, and LL of the ordinary chondrites. The relative area of olivine/pyroxene of (2.53 ± 0.04) deduced from our measurements will fit the Al Zarnkh meteorite in the LL zone of their one-dimensional plot.

The hyperfine interaction parameters in Table 2 are similar to that of previously studied ordinary chondrite meteorites (Gismelseed et al. 1994; Abdu et al. 1997; 2002), one of which is the Al Kidirate meteorite, recovered in 1983 in the western region of Sudan. It contains ~19% (in mole fraction) of fayalite and ~16% of ferrosilite and has been classified as type H6 ordinary chondrite. The second, the New Halfa meteorite, was recovered in 1994 in the eastern region of Sudan. It contains ~23.5% of fayalite and 23.2% of ferrosilite, and was classified as an L4 chondrite. Using the data obtained from the microprobe analysis, the mole fractions of fayalite and ferrosilite in the Al Zarnkh meteorite are found to be 28% and 23%, respectively, which is higher in fayalite compared to the values obtained from the other two meteorites.

Table 3. Compositions (wt%) in chromites from H, L ordinary chondrites, and the Al Zarnkh meteorite.

| Group | FeO | $TiO_2$ | $AlO_3$ | MgO | $Cr_2O_3$ |
|---|---|---|---|---|---|
| H5/6[a] | 29.12 | 2.17 | 6.45 | 3.03 | 56.7 |
| L5/6[a] | 30.16 | 2.73 | 5.86 | 2.73 | 56.0 |
| LL5[b] | 31.60 | 3.22 | 5.84 | 2.11 | 55.2 |

[a]Data from Schmitz et al. (2001).
[b]Present work.

The microprobe data and Mössbauer parameters also suggest that the troilite has an identical composition to that of the Al Kidirate and New Halfa meteorites, while the kamacite has shown 2% less Fe, which appears to have been substituted by ~2% of Co. In Table 3, we used the chromites compositions determined in the Al Zarnkh meteorite to support its classifications. The FeO and $TiO_2$ values for L5/6 chondrites are generally larger than those for H5/6 chondrites (Schmitz B et al. 2001). For the Al Zarnkh chondrite, these values are even larger than those for L5/6, which suggests that its classification be LL5/6. Similar conclusions can be derived from $AlO_3$ and MgO, in which the values are smaller in L5/6 than in H5/6, and in Al Zarnkh, the values are smaller still. In addition, the clarity of chondritic texture of Al Zarnkh, the visibility of the plagioclase, and the homogeneities of both olivine and pyroxene show that the meteorite belongs to the petrologic type 5 (Schmitz et al. 2001; Bevan et al. 2001).

## CONCLUSION

The studied meteorite consists of olivine (the most abundant), orthopyroxene, clinopyroxene, plagioclase, troilite, kamacite, and chromites phases. The microprobe data analysis found 28% of fayalite in olivine and 23% of ferrisilite in orthopyroxene, which classify the meteorite as an LL5-chondrite. The findings of Al Zarnkh together with those obtained for the Al Kidirate and New Halfa meteorites completed the classification set {H, L, LL} of ordinary chondrites. Further work on the comparison of the three meteorites could tell a great deal about their parents since each of them have a completely different history of formation.

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