Beni M’hiria: A new chondritic (L6) meteorite fall from Tunisia

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(Received 6 March 2003; revision accepted 17 July 2003)

Abstract—The Beni M’hiria meteorite fell on January 8, 2001 in southeastern Tunisia. This is only the fifth observed fall from Tunisia. On the basis of mineralogical, petrographic, and geochemical data, the stone can be classified as an L6 chondrite of shock stage S5.

INTRODUCTION

In meteoritics and planetary sciences, fresh meteorite falls are of fundamental importance because they represent reference material for mineralogical, geochemical, and geophysical analyses.

In this work, we report on the latest (2001) observed fall from Tunisia, named Beni M’hiria (Russell et al. 2003), providing first-hand information on the circumstances of the fall and classification based on mineralogical composition, bulk chemistry, and magnetic properties.

THE FALL

At 3:00 p.m. (local time) on January 8, 2001, a meteorite fell in the Beni M’hiria region in southeastern Tunisia (Fig. 1). The fall was witnessed by the inhabitants of Ksar Beni M’hira (~32°52' N 10°48' E), a small village ~35 km east of Foum Tataouine, a place well-known in meteoritics as “Tatahouine.” After the appearance of a fireball accompanied by detonations, the meteoroid hit unpaved ground, generating a small pit ~15 cm wide and deep. On impact with the ground, the meteorite broke into three pieces, weighing 1.720, 0.300, and 0.200 kg and each partially covered by a thin, matt-black fusion crust. The three masses were found by a local shepherd and consigned to the Garde National. After being inspected by officers at the Ministère des Affaires Intérieures, the three stony fragments were sent to the Département de Géologie of Tunis Faculty of Science for curation and initial petrographic characterization. An additional 7 pieces totalling >14 kg were later recovered by private finders in April 2001. The specimens in well-curated collections are: 2190 g, Tunis Faculty of Science; 29.2 g, Pisa University’s Museo di Storia Naturale; 467.7 g (from the late recoveries), Museum National d’Histoire Naturelle, Paris, France.

SAMPLES AND ANALYTICAL METHODS

A partially (40%) fusion crusted, 50 × 33 × 21 mm fragment of 1720 g piece was used in this study (Fig. 2). The broken surface reveals a light, grey coloured interior speckled with bright, sub-mm-sized metal and sulfide particles. A few large chondrules up to 5 mm in diameter are set in a homogeneous matrix, crosscut by a network of dark, shock veinlets. A mm-sized, pink-brown coloured, rounded bleb with a glassy appearance represents a peculiar feature of the Beni M’hiria sample (Fig. 3a). The overall sample appears very fresh at the hand specimen scale.

Three polished thin sections (BM,01, ,02, and ,03) totalling ~2.3 cm² were obtained from a 2.5 g chip for petrographic investigation by optical microscopy and scanning electron microscopy (SEM). SEM studies were carried out using a Philips XL30 SEM located at Pisa University’s Dipartimento di Scienze della Terra. Mineral compositions were determined with a JEOL JXA 8600 electron microprobe at the Istituto di Geoscienze e Georisorse, C.N.R., Florence. A fragment of the pink-brown inclusion was also hand-picked for electron microprobe and X-ray powder diffraction analyses.

The modal content of metal and sulfide was determined through digital image analyses (using the Image-Pro Plus 4.5
software package) of reflected light images of thin sections taken under the optical microscope. The mode of the remaining phases was determined through X-ray powder diffraction data using the Rietveld method (e.g., Rietveld 1969; Hill and Howard 1987; Young 1993; Bish and Post 1993). The Rietveld method does not suffer from the problems of image analysis, namely, a low color contrast between silicate phases, grain size commensurate with the image resolution, presence of oriented spatial distribution in the section, and especially, the occurrence of amorphous phases. Nearly one gram of rock was hand-ground in an agate mortar to a grain size of nearly 10 \( \mu \text{m} \) and then the magnetic phases were removed using a strong magnet. The remaining powder was then spiked and homogenized with 9.26% wt% of NIST SRM 674a rutile as an internal standard. The use of this standard allows the refinement of both the zero and displacement corrections and the detection of the presence of amorphous materials. X-ray data for the Rietveld study were collected using a Philips PW1050/1710 Bragg-Brentano diffractometer, with graphite monocratomized CuK\( \alpha \) radiation, at Pisa University’s Dipartimento di Scienze della Terra. The spectrum was acquired with an overnight scan recorded in the range of 13–80° 2\( \theta \) with 0.02° steps and a 17 sec counting time. Rietveld refinement was carried out using the GSAS/EXPGUI program (Larson and Von Dreele 1995; Toby 2001). The final agreement factors were \( R_p = 9.27\% \), \( R_{wp} = 12.24\% \), and \( R_F^2 = 8.93\% \). A 2.30 g fragment was finely hand-ground in an agate mortar for bulk chemical analyses performed at Pisa University’s Dipartimento di Scienze della Terra. An aliquot of 625 mg was ignited at 1000 °C for 1 hr for the determination of loss on ignition (LOI) and then fluxed with an excess of Li\( \text{B}_2\text{O}_3 \) (1:7 weight ratio) for SiO\( _2 \), TiO\( _2 \), Al\( \text{O}_3 \), Cr\( \text{O}_3 \), Fe\( \text{O}_{\text{tot}} \), Mn\( \text{O} \), Mg\( \text{O} \), Ca\( \text{O} \), Na\( \text{O} \), K\( \text{O} \), and P\( \text{O}_5 \) determination by XRF (ARL 9400 XP\( ^+ \)). The estimated precisions for major element data in the concentration ranges of 1–50 wt% and 0.1–1 wt% are better than 2% and better than 10%, respectively.

The concentration of an additional 37 elements was determined by ICP-MS (Fisons PQII + STE). Two powder aliquots of 82 and 101 mg, respectively, were dissolved in PFA vessels on a hot plate at 120 °C, by using a mixture of HF + HNO\( _3 \) purified by subboiling distillation. After adding 20 ng ml\( ^-1 \) of Rh, Re, and Bi as internal standards, the sample solutions, at \( \sim 1:500 \) dilution, were measured in replicates by external calibration. The measurements were corrected for drift, blank contribution, and isobaric interferences. Analytical precision is generally better than 5% for concentrations \( \geq 1 \mu \text{g g}^{-1} \), while it varies between 5 and 15% in the concentration range of 0.01–1.0 \( \mu \text{g g}^{-1} \).

Magnetic properties were measured on several fragments to fit this new fall into the magnetic classification scheme of Rochette et al. (2003) by using a Kappabridge magnetic susceptibility meter and a 2G cryogenic remanometer with inline alternating field magnetization at the Centre Européen de Recherche et d’Enseignement de Géosciences de l’Environnement (CEREGE), Aix en Provence, France.

PETROGRAPHY AND MINERAL CHEMISTRY

Beni M’hira shows a medium to coarsely recrystallized granoblastic texture with few poorly defined, barred olivine, porphyritic olivine, and granular olivine-pyroxene relic chondrules up to several mm in diameter (Fig. 3b). The major minerals are olivine, orthoenstatite, Fe,Ni metal (kamacite and minor taenite), maskelynite (plagioclase transformed into diaplectic glass by shock deformation) of oligoclase composition, augite, and troilite. The accessory minerals include chromite, merrillite, chlorapatite, and ilmenite. The mineral mode is: olivine 43.6 vol%; orthoenstatite 27.7%; oligoclase 11.0% (8.4% maskelynite inclusive); augite 7.2%; troilite 5.2%; Fe,Ni metal 4.1%; chromite 0.7%; and phosphates 0.4% (Table 1).

Representative electron microprobe analyses are given in Table 2. All minerals, except maskelynitized plagioclase, show homogenous chemical compositions typical of equilibrated ordinary chondrites (e.g., Dodd 1981; Sears and Dodd 1988; Brearley and Jones 1998). The fayalite mol% in olivine is Fa\( _{23.3} \) and the ferrosilite mol% in enstatite is Fs\( _{21.4} \). Thus, Beni M’hira belongs to the L-class of the ordinary chondrites, following the classification criteria for ordinary chondrites first proposed by Van Schmus and Wood (1967). The major and minor element compositions of the other
The Beni M’hira chondrite minerals are consistent with the compositional ranges for equilibrated L chondrites (Brearley and Jones 1998). Maskelynite has a rather variable oligoclase composition; as reported in Table 2, the typical composition is K-poor, An_{10.5}Or_{1.3}, unlike many equilibrated L chondrites (Brearley and Jones 1998); nevertheless, some grains gave normal values around An_{12}Or_{10}. Shock-induced mobilization of alkalis during shock metamorphism is a possible explanation for the observed variable compositions.

As is the case for many L chondrites (Stöffler et al. 1991; Bennett and McSween 1996), Beni M’hira exhibits petrographic evidence characteristic of strong shock metamorphism: mosaicism, planar fractures and planar deformation features in olivine, maskelynitized plagioclase, polycrystalline troilite, and coarse plessitic textures in metal grains. Further evidence for strong shock includes fracturing and undulose (often fan-like) extinction in pyroxene and a network of crosscutting shock veinlets. Shock veins, up to several tens of μm thick, mainly consist of glass and coalescent metal and sulfide droplets, often intergrown in cellular textures. Shock veins may also show clastic structures, isolating fragments of the host chondrite. Some lateral displacement indicative of shear stress is observed along few veins. Beni M’hira is a strongly shocked, shock stage S5, chondrite after the classification scheme for ordinary chondrites by Stöffler et al. (1991).

In thin section, weathering is very minor with only occasional, brown-yellow, limonitic staining in mafic silicates around few metal particles, which likely developed during sample preparation. According to the classification scheme proposed by Wlotzka (1993) for the weathering grade of ordinary chondrites, Beni M’hira belongs to the W0 class, typical of fresh falls.

The pink-brown bleb shown in Fig. 3a consists of
completely amorphous glass with a non-stoichiometric, feldspathic (SiO$_2$ = 64.37, Al$_2$O$_3$ = 25.71, CaO = 4.52, Na$_2$O = 5.26, and K$_2$O = 0.76 wt%) composition, according to X-ray diffraction and electron microprobe data. The few weak reflections of the linnaeite sulfide group observed in its diffraction pattern may be from tiny opaque inclusions. The opaque rim of the glass inclusion (Fig. 3a) consists of submicrometric grains of chromite, as revealed by electron microprobe analyses.

**BULK CHEMICAL COMPOSITION**

The major and trace element composition of Beni M’hira (Table 3) falls within the typical range of L chondrites (Wasson and Kallemeyn 1988; Jarosevich 1990; Fig. 4). In particular, the key elemental ratios Mg/Si, Al/Si, Ca/Si, Ca/Al, and Fe(t)/Si are nearly concident with the average values for L chondrites (Table 3, third column). The highly mobile elements Cs, Rb, K, Ba, Na, and U, easily added to stony meteorites during hot desert weathering, are chondritic, confirming the absolute freshness of Beni M’hira.

In the diagram of Fig. 4b, it can be observed that Sn, the most volatile chalchophile element determined, is depleted with respect to the average L chondrite, while W, the most refractory element, is slightly enriched, as a possible consequence of shock-induced mobilization of metal and sulfide components.

Major-element XRF data can be conveniently cross-

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**Table 1. Modal composition of Beni M’hira and other equilibrated ordinary chondrites.**

<table>
<thead>
<tr>
<th></th>
<th>Beni M’hira$^a$</th>
<th>Hashima$^b$</th>
<th>Devri-Khera$^c$</th>
<th>Sabrum$^d$</th>
<th>Normative mineralogy of avg. L chondrite$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L6</td>
<td>H4</td>
<td>L6</td>
<td>LL6</td>
<td>wt%</td>
</tr>
<tr>
<td>Olivine</td>
<td>42.4</td>
<td>35.3</td>
<td>44</td>
<td>55.9</td>
<td>Olivine 45.0</td>
</tr>
<tr>
<td>Enstatite</td>
<td>26.1</td>
<td>44.6</td>
<td>30</td>
<td>20.6</td>
<td>Hypersthene 24.0</td>
</tr>
<tr>
<td>Fe,Ni metal</td>
<td>8.9</td>
<td>8.2</td>
<td>2.5</td>
<td>1.7</td>
<td>Fe,Ni metal 8.3</td>
</tr>
<tr>
<td>Troilite</td>
<td>6.7</td>
<td>5.8</td>
<td>5</td>
<td>6.9</td>
<td>Troilite 5.8</td>
</tr>
<tr>
<td>Augite</td>
<td>6.6</td>
<td>3</td>
<td>2.3</td>
<td></td>
<td>Diopside 5.0</td>
</tr>
<tr>
<td>Maskelynite</td>
<td>6.0</td>
<td>13</td>
<td>10.9</td>
<td></td>
<td>Feldspar 10.3</td>
</tr>
<tr>
<td>Oligoclase</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
<td>Chromite 0.8</td>
</tr>
<tr>
<td>Chromite</td>
<td>0.9</td>
<td>&lt;0.1</td>
<td>1</td>
<td>1.7</td>
<td>Apatite 0.5</td>
</tr>
<tr>
<td>Phosphates</td>
<td>0.4</td>
<td>&lt;0.1</td>
<td>&lt;1</td>
<td></td>
<td>Ilmenite 0.2</td>
</tr>
</tbody>
</table>

$^a$This study.


$^c$Ghosh et al. (2001).

$^d$Ghosh et al. (2002).


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**Table 2. Representative electron microprobe analyses (wt%) of major phases in Beni M’hira.$^a$**

|        | Olivine | Enstatite | Augite | Oligoclase | Chrome | Cl-apatite | Merrillite | Kamacite | Taenite | Trolite | SiO$_2$ | TiO$_2$ | Al$_2$O$_3$ | FeO | CoO | NiO | MnO | MgO | CaO | FeO | Cl | P | Total |
|--------|---------|-----------|--------|-----------|--------|-----------|------------|----------|---------|--------|---------|--------|----------|------|-----|-----|-----|-----|-----|-----|-----|---|---|-------|
|        |         |           |        |           |        |           |            |          |         |        |         |        |          |      |     |     |     |     |     |     |     |---|---|-------|
|        | 38.26   | <0.04     | <0.04  | <0.04     | <0.04  | <0.04     | <0.04      | <0.04    | <0.04   | <0.04  | <0.04   | <0.04  | <0.04    |      |     |     |     |     |     |     |     |---|---|-------|
|        | 55.71   | 0.2       | <0.04  | 0.04      | 2.72   | <0.04     | <0.04      | <0.04    | <0.04   | <0.04  | <0.04   | <0.04  | <0.04    |      |     |     |     |     |     |     |     |---|---|-------|
|        | 4.15    | 0.13      | 6.12   | 0.2       | 31.88  | 0.2       | 0.74       | <0.05    | <0.05   | <0.05  | <0.05   | <0.05  | <0.05    |      |     |     |     |     |     |     |     |---|---|-------|
|        | 10.4    | <0.05     | <0.05  | 55.39     | <0.05  | <0.05     | <0.05      | Total    | 100.18  | 100.22 | 98.63   |        |          |      |     |     |     |     |     |     |     |---|---|-------|
|        | 0.52    | 10.14     |        | 0.23      | 0.23   | <0.02     | <0.02      | <0.02    | <0.02   | <0.02  | <0.02   | <0.02  | <0.02    |      |     |     |     |     |     |     |     |---|---|-------|
|        | <0.02   | <0.02     | <0.02  | <0.02     | <0.02  | 1         | 0.51       | <0.02    | <0.02   | <0.02  | <0.02   | <0.02  | <0.02    |      |     |     |     |     |     |     |     |---|---|-------|
|        | 5.59    | 42.18     | 46.88  | 42.18     | 46.88  | Total     | 101.86     | 99.82    |         |        |         |        |          |      |     |     |     |     |     |     |     |---|---|-------|
| End member |        | F         | Cl     | P$_2$O$_5$ | Total   |           |            |          |         |        |         |        |          |      |     |     |     |     |     |     |     |---|---|-------|
| End member |        |            |        |           |        |           |            |          |         |        |         |        |          |      |     |     |     |     |     |     |     |---|---|-------|

$^a$Blank = not determined.
linked with the results of the combined Rietveld-Image analysis modal determination. Assuming that the amorphous phase detected by the Rietveld method has the same composition as oligoclase, and using the mineral phase compositions determined by microprobe (Table 2), we can recalculate a bulk chemical analysis (reported in the second column of Table 3). Apart from small discrepancies, which can be ascribed to minor inaccuracies of the modeling, the results are quite satisfactory and confirm both the accuracy of all the involved experimental data and the soundness of our combined Rietveld-Image analysis approach.

**MAGNETIC PROPERTIES**

Following Rochette et al. (2003), Beni M’hira shows magnetic properties diagnostic for L chondrites. The magnetic susceptibility, expressed as the decimal logarithm of apparent mass specific susceptibility $\chi$ (in $10^{-9}$ m$^3$/kg), is...
log\chi = 5.01 \pm 0.02. This value is consistent with the highest values for L6 chondrites (log\chi = 4.86 \pm 0.11; based on 108 meteorite falls). Saturation remanence (M_{rs}, in 10^{-3} Am^2/kg) gives a logM_{rs} of 1.58, which is comparable with the lowest values for L chondrites (2.12 \pm 0.45; based on 22 falls).

The intensity of natural remanence magnetization (NRM) is 1.15 \times 10^{-3} Am^2/kg. Alternating field demagnetization reveals an extremely soft NRM: median destructive field (MDF) is less than 1 mT, and the intensity is reduced to 5.7 \times 10^{-5} Am^2/kg at 10 mT. It is practically constant above this field. As M_{rs} is much harder (MDF of 7 mT), the REM ratio (1000 \times NRM/M_{rs}), symptomatic of the NRM acquisition process (Wasilewski and Dickinson 2000), decreases from an initial value of 30 to a value of 3.8 at 10 mT, which is more likely to be representative of extraterrestrial magnetization.

**CONCLUSIONS**

1. The Beni M’hira meteorite fall was witnessed at 3:00 p.m. (local time) on January 8, 2001 by the inhabitants of Ksar Beni M’hira, a small village ~35 km east of Foum Tataouine in southeastern Tunisia. Three fragments, for a total of 2.2 kg, were recovered. An additional 7 pieces totalling >14 kg were later recovered by private finders in April 2001.

2. Beni M’hira is classified as a strongly shocked (shock
Table 4. Meteorites from Tunisia.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date of fall</th>
<th>Lat. N</th>
<th>Long. E</th>
<th>Class</th>
<th>Recovered weight</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatahouine</td>
<td>June 27, 1931</td>
<td>32°57′</td>
<td>10°25′</td>
<td>Achondrite diogenite</td>
<td>~12 kg</td>
<td>Grady (2000)</td>
</tr>
<tr>
<td>Dahmani</td>
<td>May 1981</td>
<td>~35°37′</td>
<td>~08°50′</td>
<td>Ordinary chondrite</td>
<td>~18 kg</td>
<td>Grady (2000)</td>
</tr>
<tr>
<td>Sfax</td>
<td>October 16, 1989</td>
<td>34°45′</td>
<td>10°43′</td>
<td>Ordinary chondrite</td>
<td>&gt;4.7 kg</td>
<td>Grady (2000)</td>
</tr>
<tr>
<td>Djoumine</td>
<td>October 31, 1999</td>
<td>36°57′</td>
<td>09°33′</td>
<td>Ordinary chondrite</td>
<td>~10 kg</td>
<td>Grossman (2000)</td>
</tr>
<tr>
<td>Beni M’hira</td>
<td>January 8, 2001</td>
<td>~32°52′</td>
<td>~10°48′</td>
<td>Ordinary chondrite</td>
<td>&gt;16.2 kg</td>
<td>This study</td>
</tr>
</tbody>
</table>

Acknowledgments—Filippo Olmi is thanked for assistance during electron microprobe analyses at the CNR Istituto di Geoscienze e Georisorse in Florence. Marco Tamponi is thanked for the XRF analyses of the bulk rock at Pisa University’s Dipartimento di Scienze della Terra. Paul Benoit and an anonymous referee are thanked for reviews and Timothy Jull and Denis Shaw are thanked for editorial assistance. Financial support was provided by the Italian Ministero dell’Università e della Ricerca (MIUR) and the Italian Programma Nazionale delle Ricerche in Antartide (PNRA).

Editors Handling—Dr. Denis Shaw and Dr. Timothy Jull

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