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Beni M'hira: A new chondritic (L6) meteorite fall from Tunisia

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Abstract–The Beni M'hira 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'hira (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'hira 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 Départment 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 34.0 g from the 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'hira 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 cm^2 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

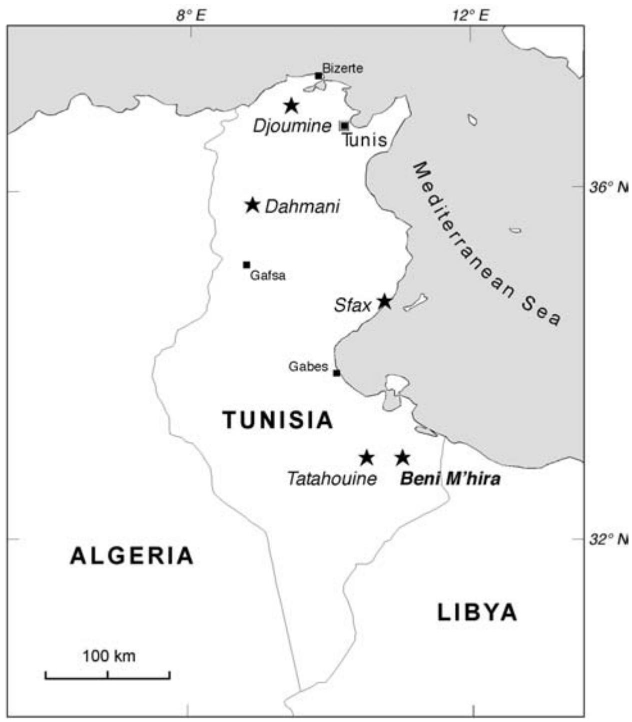

Fig. 1. Sketch map of Tunisia showing locations (stars) of the Beni M'hira fall and other Tunisian meteorites.

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 μm 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 monocromatized CuKα 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° 2θ 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 $Li_2B_4O_7$ (1:7 weight ratio) for SiO_2, TiO_2, Al_2O_3, Cr_2O_3, FeO_{tot}, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_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 ~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 >1 μg g^{-1}, while it varies between 5 and 15% in the concentration range of 0.01–1.0 μg 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'Environment (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, chloroapatite, 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 $Fa_{24.3}$ 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

Fig. 2. The fragment of the Beni M'hira L6 chondrite studied in this work showing thin, matt-black fusion crust and fresh, light grey interior.

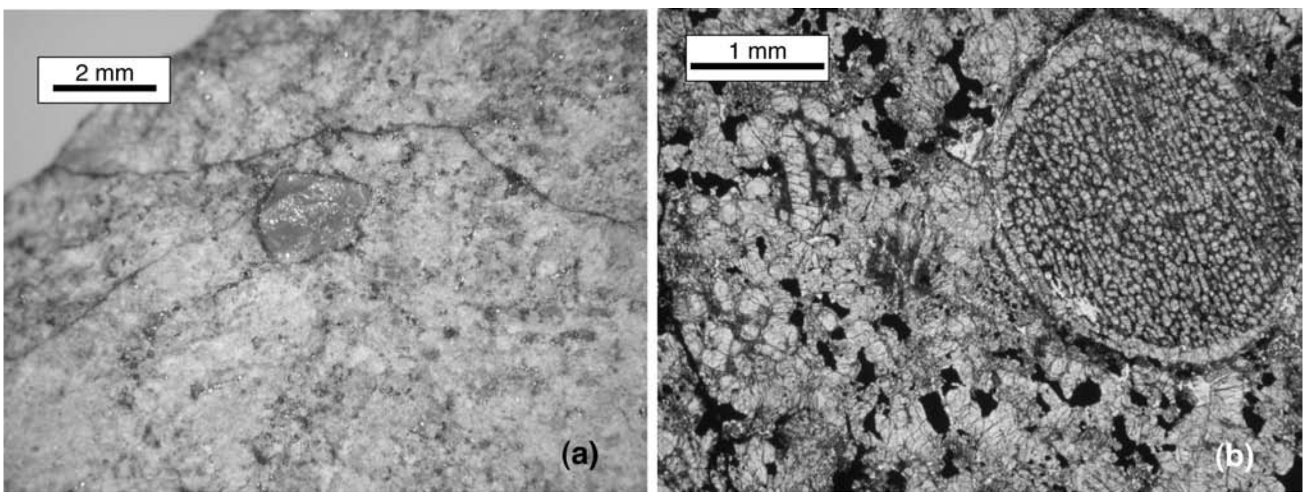

Fig. 3. a) Stereomicrophotograph of a freshly broken surface of Beni M'hira showing a 2 mm-sized glass inclusion set in a homogeneous crystalline matrix crosscut by dark shock veinlets; b) transmitted light photomicrograph of Beni M'hira showing a mm-sized, highly recrystallized, barred olivine chondrule relic set in a granoblastic matrix.

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

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

	Beni M'hira[a]			Hashima[b]	Devri-Khera[c]	Sabrum[d]	Normative mineralogy	
	L6			H4	L6	LL6	of avg. L chondrite[e]	
	wt%	vol%		vol%	vol%	vol%		wt%
Olivine	42.4	43.6	Olivine	35.3	44	55.9	Olivine	45.0
Enstatite	26.1	27.7	Enstatite	44.6	30	20.6	Hypersthene	24.0
Fe,Ni metal	8.9	4.1	Fe,Ni metal	8.2	2.5	1.7	Fe,Ni metal	8.3
Troilite	6.7	5.2	Troilite	5.8	5	6.9	Troilite	5.8
Augite	6.6	7.2	Augite	–	3	2.3	Diopside	5.0
Maskelynite	6.0	8.4	Plagioclase	–	13	10.9	Feldspar	10.3
Oligoclase	1.9	2.6		–	–	–	Chromite	0.8
Chromite	0.9	0.7	Spinel	<0.1	1	1.7	Apatite	0.5
Phosphates	0.4	0.4	Phosphates	<0.1	<1		Ilmenite	0.2
Ilmenite	Traces	Traces						

[a]This study.
[b]Hoshino and Suwa (1992).
[c]Ghosh et al. (2001).
[d]Ghosh et al. (2002.
[e]Normative composition of the average L chondrite of Jarosevich (1990).

Table 2. Representative electron microprobe analyses (wt%) of major phases in Beni M'hira.[a]

	Olivine	Enstatite	Augite	Oligoclase	Chromite	Cl-apatite	Merrillite		Kamacite	Taenite	Troilite
SiO_2	38.26	55.71	54.16	65.25	<0.07	<0.07	<0.07	Fe	93.21	69.02	62.66
TiO_2	<0.04	0.2	<0.04	0.04	2.72	<0.04	<0.04	Co	0.91	0.35	0.05
Al_2O_3	<0.04	0.15	<0.04	22.76	6.12	<0.04	<0.04	Ni	6.07	30.85	0.03
FeO	22.50	13.61	4.15	0.13	31.88	0.2	0.74	Cr	<0.05	<0.05	0.04
MnO	0.49	0.51	0.24	<0.07	0.72	<0.07	<0.07	Mn	<0.07	<0.07	
MgO	38.09	28.34	16.38	<0.06	2.41	<0.06	3.78	P	<0.03	<0.03	
CaO	0.30	0.66	22.34	2.18	0.1	52.4	45.35	Cl	<0.02	<0.02	<0.02
NiO	0.06							S			35.92
Cr_2O_3	<0.05	<0.05	0.66	<0.05	55.39	<0.05	<0.05	Total	100.18	100.22	98.63
CoO	<0.04										
Na_2O			0.52	10.14		0.49	2.51				
K_2O		<0.02	<0.02	0.23		<0.02	0.06				
F						1	0.51				
Cl						5.59	<0.02				
P_2O_5						42.18	46.88				
Total	99.74	99.54	99.35	100.73	99.34	101.86	99.82				
End member	$Fo_{75.7}$	$En_{77.3}$ $Wo_{1.3}$	$En_{46.9}$ $Wo_{46.0}$	$An_{10.5}$ $Or_{1.3}$	$Ulvö_{7.4}$ $Sp_{12.9}$ $Chr_{78.5}$ $Mag_{1.3}$						

[a]Blank = not determined.

completely amorphous glass with a non-stoichiometric, feldspathic (SiO_2 = 64.37, Al_2O_3 = 25.71, CaO = 4.52, Na_2O = 5.26, and K_2O= 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-

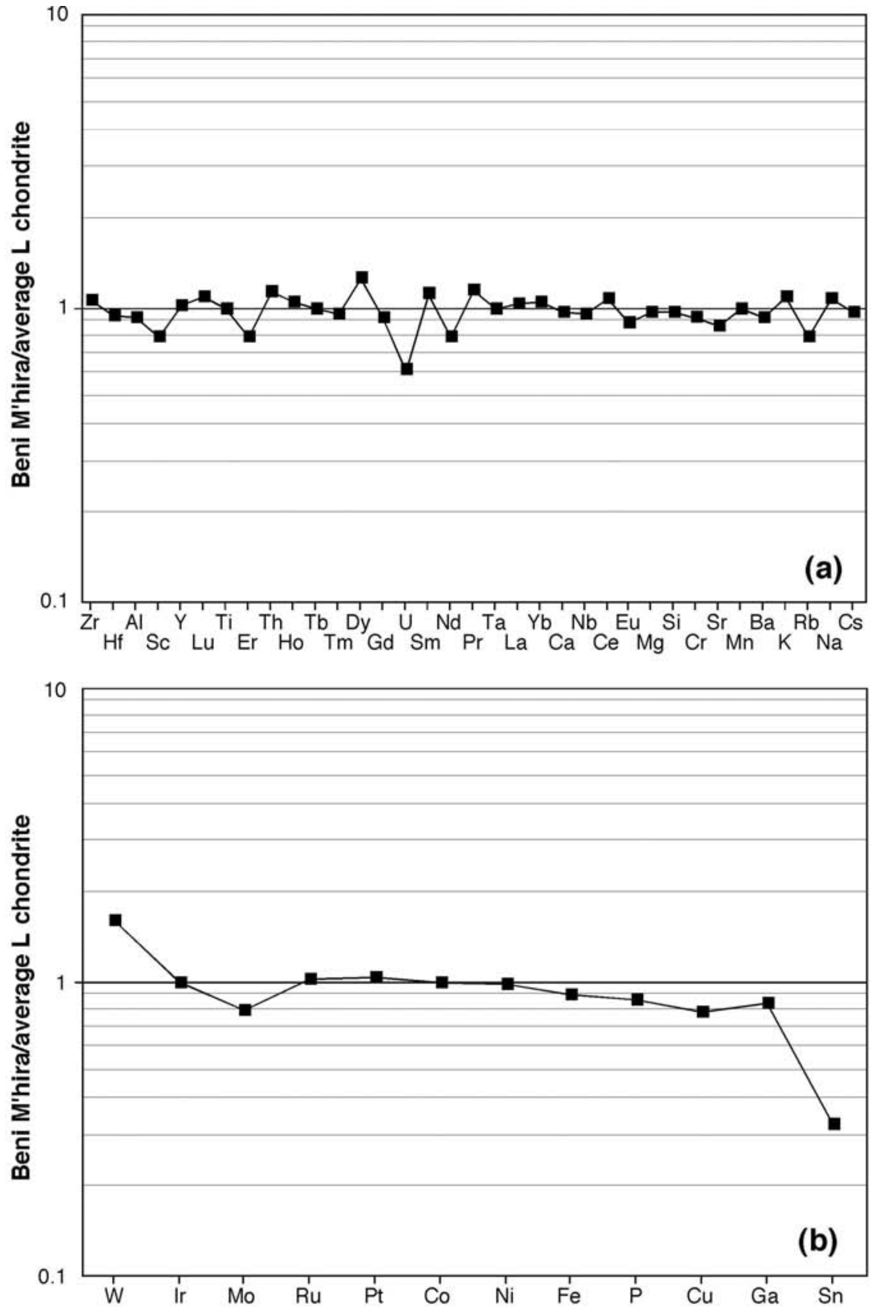

Fig. 4. L chondrite-normalized lithophile (a) and siderophile + chalcophile elements (b). In both diagrams, elements are arranged from left to right in order of decreasing 50% condensation temperature (at 10^{-6} atm). The normalizing values are after Wasson and Kallemeyn (1988) and Jarosevich (1990).

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 χ (in 10^{-9} m^3/kg), is

Table 3. Bulk chemistry of Beni M'hira.

	Beni M'hira[a]	Beni M'hira (Recalculated)[b]	Average L chondrite (Jarosevich 1990)		Beni M'hira[a]	Average L chondrite (Wasson and Kallemeyn 1988)
Oxide phase				Trace elements		
SiO_2 (wt%)	38.38	39.68	39.72	Sc (mg g-1)	6.9	8.6
TiO2	0.12	0.08	0.12	Cu	71	90
Al2O3	2.1	1.9	2.25	Ga	4.8	5.7
Cr2O3	0.50	0.57	0.53	Rb	2.49	3.1
FeO	25.6[c]	13.73	14.46	Sr	9.6	11.1
MnO	0.34	0.37	0.34	Y	2.14	2.1
MgO	23.87	24.75	24.73	Zr	5.3	5.0
CaO	1.8	2.2	1.85	Nb	0.37	0.39
Na2O	1.02	0.84	0.95	Mo	1.04	1.3
K2O	0.12	0.02	0.11	Ru	0.80	0.78
P2O5	0.19	0.17	0.22	Sn	0.23	0.71
				Cs	0.027	0.028[d]
LOI	–4.23			Ba	3.4	3.7
				La	0.32	0.31
Metallic phase				Ce	0.97	0.90
Fe (wt%)		8.35	7.03	Pr	0.14	0.122
Ni	1.22[e]		1.24	Nd	0.66	0.82
Co	0.06[e]		0.06	Sm	0.22	0.195
				Eu	0.07	0.078
Sulfide phase				Gd	0.29	0.31
Fe (wt%)		4.14	3.66	Tb	0.057	0.057
S		2.5	2.1	Dy	0.38	0.30
				Ho	0.085	0.081
Elemental ratios				Er	0.24	0.298
Mg/Si	0.80	0.80	0.80	Tm	0.037	0.039
Al/Si	0.062	0.055	0.064	Yb	0.23	0.22
Ca/Si	0.072	0.084	0.071	Lu	0.036	0.033
Fe(t)/Si	1.11	1.25	1.18	Hf	0.16	0.17
Ca/Al	1.16	1.53	1.12	Ta	0.023	0.023
Fe(t)/Ni	16.3		17.7	W	0.18	0.11
Fe(m)/Fe(t)		0.36	0.32	Ir	0.49	0.49
				Pt	1.08	1.05
				Th	0.049	0.043
				U	0.008	0.013

[a]Average of two replicates.
[b]Recalculated on the basis of modal composition and mineral chemistry.
[c]Total iron calculated as FeO.
[d]Cs content from Lingner (1985).
[e]All Ni and Co are arbitrarily assigned to the metal phase.

$\log\chi = 5.01 \pm 0.02$. 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 $\log M_{rs}$ of 1.58, which is comparable with the lowest values for L chondrites (2.12 ± 0.45; based on 22 falls).

The intensity of natural remanence magnetization (NRM) is 1.15×10^{-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 5.7×10^{-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.

Name	Date of fall	Lat. N	Long. E	Class	Recovered weight	Reference
Tatahouine	June 27, 1931	32°57′	10°25′	Achondrite diogenite	~12 kg	Grady (2000)
Dahmani	May 1981	~35°37′	~08°50′	Ordinary chondrite (LL6)	~18 kg	Grady (2000)
Sfax	October 16, 1989	34°45′	10°43′	Ordinary chondrite (LL6)	>4.7 kg	Grady (2000)
Djoumine	October 31, 1999	36°57′	09°33′	Ordinary chondrite (H5–6)	~10 kg	Grossman (2000)
Beni M'hira	January 8, 2001	~32°52′	~10°48′	Ordinary chondrite (L6)	>16.2 kg	This study

stage S5) L6 ordinary chondrite on the basis of mineralogical, petrographic, and geochemical data and magnetic properties.

3. Beni M'hira is the fifth observed fall (and the fifth meteorite in total) recovered from Tunisia (Table 4) after the Djoumine H5–6 (1999), the Sfax L6 (1989), the Dahmani LL6 (1981), and the Tatahouine diogenite (1931).

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