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The effect of terrestrial weathering on the magnetic properties of meteorites from the Atacama Desert

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Abstract

Once ordinary chondrites fall on Earth, Fe–Ni minerals and troilite they contain oxidize and transform into iron oxyhydroxides and/or iron oxides, which is expected to modify their magnetic properties. In this study, the effect of long-term terrestrial weathering on the magnetic properties (magnetic susceptibility and hysteresis parameters) of 117 H and L ordinary chondrites from the Atacama Desert (Chile), a region hosting the oldest meteorite collection in the world, was investigated. The measurements revealed a consistent weathering-induced decrease in the saturation magnetization and magnetic susceptibility of both H and L chondrites. The observed trends indicate a faster initial weathering of Fe–Ni minerals compared to troilite, their transformation into mostly paramagnetic iron oxyhydroxides, as well as the formation of magnetite in the later weathering stages.

Keywords: ordinary chondrites, terrestrial weathering, magnetic properties, magnetic susceptibility, hysteresis, Atacama Desert

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Влияние земного выветривания на магнитные свойства метеоритов из пустыни Атакама

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Аннотация

После падения на Землю обыкновенных хондритов, содержащиеся в них минералы Fe и Ni, а также троилит подвергаются окислению и преобразуются в оксигидроксиды и/или оксиды железа. Предполагается, что эти изменения влияют на их магнитные свойства. В работе представлены результаты изучения воздействия длительного выветривания на магнитные свойства (магнитную восприимчивость и гистерезисные параметры) 117 обыкновенных хондритов групп H и L, собранных в пустыне Атакама (Чили), на территории которой сосредоточено одно их древнейших в мире скоплений метеоритов. Установлено, что намагниченность насыщения и магнитная восприимчивость метеоритов обеих групп уменьшаются с увеличением степени выветривания. Выявленные зависимости указывают на то, что минералы Fe и Ni более подвержены выветриванию, по сравнению с троилитом. При этом они в основном превращаются в парамагнитные оксигидроксиды железа, а магнетит образуется на более поздних стадиях выветривания.

Ключевые слова: обыкновенные хондриты, земное выветривание, магнитные свойства, магнитная восприимчивость, гистерезис, пустыня Атакама.

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Introduction

Meteorites are asteroid fragments, with only a small fraction coming from the Moon and Mars. The most abundant type of meteorites falling on Earth are ordinary chondrites originating from different parent bodies and divided into three groups (H, L, and LL) based on variations in chemical composition [1]. They normally contain silicate minerals (olivine, pyroxene, plagioclase), Fe–Ni minerals (kamacite, taenite, tetrataenite), and iron sulfides (troilite). Silicate minerals are resistant to chemical alternation in terrestrial settings. Fe–Ni minerals and troilite oxidize while the meteorite sits on the surface of Earth, and, before it is collected and properly stored in a dry place, this process leads to the formation of iron oxyhydroxides (lepidocrocite, akaganeite, goethite) and/or iron oxides (magnetite and maghemite) [2, 3].

Most meteorites have been recovered from Antarctica or hot deserts. Antarctic meteorites are relatively well preserved from terrestrial weathering because they spend most of their time on Earth embedded in the ice, which limits their interaction with liquid water. In contrast, hot desert meteorites are often strongly weathered due to moisture effects and terrestrial processes like rain [e.g., 4, 5]. The Atacama Desert, in Chile, stands out among other hot deserts for its exceptionally stable and extreme hyperaridity [6]. It hosts the oldest meteorite collection in the world. In the El Médano dense collection area, the average terrestrial age of meteorites is 710 k.y. [7]. Broadly similar terrestrial ages have been reported for the Catalina, Calama, Chug Chug, and Sierra Gorda dense collection areas [8].

The magnetic properties of ordinary chondrites are defined by the abundance and nature of Fe–Ni minerals. Their magnetic susceptibility [9] and hysteresis characteristics [10] have been extensively studied for classification [9, 11], as well as for reconstructing thermal and shock history [10]. However, both are also sensitive to weathering and associated oxidation of metallic minerals [9, 12].

In this article, the magnetic properties of meteorites from the Atacama Desert are examined in connection with long-term weathering.

1. Material and Methods

A total of 117 Atacama meteorites, all H and L ordinary chondrites, from the meteorite collections of the European Center for Research and Teaching in Environmental Geosciences (Centre de recherche et d'enseignement des géosciences de l'environnement, CEREGE) and the Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences were studied. The samples (selected randomly) originate from four different dense collection areas (DCAs) in the Atacama Desert: the El Médano area, which includes meteorite finds from the El Médano and the Caleta el Cobre DCAs [13]; the San Juan DCA [14]; the Catalina DCA [8]; and the Calama area, a region comprising Calama, Chug Chug, and Sierra Gorda DCAs [8].

Hysteresis measurements were performed on samples in the range of 74–1357 mg, with an average mass of 435 mg (s.d. 256 mg, $n = 117$). The samples were broken from the type meteorite specimen using a rock trimmer. For comparison with unweathered meteorites, a 784 mg sample of the Tamdakht H5 chondrite and a 975 mg sample of the Sueilila 004 L6 chondrite, both from the CEREGE meteorite collection, were studied.

Hysteresis properties of the samples were measured at CEREGE and Kazan Federal University (KFU). At CEREGE, two vibrating sample magnetometers (VSM) were used, a Princeton Micromag VSM and a Lakeshore 8600 VSM (LakeShore Cryotronics, Inc., USA), to obtain hysteresis loops with a maximum field of 1 and 1.5 T, respectively, and a field step of 10 mT in both cases. At KFU, hysteresis parameters were determined using a J_meter coercive spectrometer [15, 16] with a field step of 1 mT and a maximum field of 1.5 T.

From the hysteresis loops, the following parameters were deduced: saturation magnetization (M_s), saturation remanence (M_{rs}), and coercivity (B_c). To isolate the ferromagnetic part of the hysteresis loops, the paramagnetic and diamagnetic contributions to magnetic susceptibility (estimated by a linear fit over the 0.9–1 T and 1.4–1.5 T intervals for the measurements performed with a Princeton VSM and a LakeShore 8600 VSM, respectively) were removed. Because the approach to saturation [e.g., 17] is not negligible for Fe–Ni minerals, the M_s values were corrected. For the M_s values fitted over the 0.9–1 T interval, a +19 % correction factor was applied, as outlined by Gattacceca et al. [10]. For those obtained using a linear fit over the 1.4–1.5 T interval, a +5.2 % correction factor was used. The coercivity of remanence (B_{cr}) was determined from the back-field demagnetization experiments.

The low-field magnetic susceptibility (noted χ) of a bulk meteorite sample was measured at CEREGE with a Kappabridge KLY2 (AGICO, Czech Republic) operating at 300 A/m and 920 Hz and equipped with a large coil (nominal sample volume 65 cm^3). The samples too large for this device were measured using a SM30 magnetic susceptibility meter (ZHinstruments, Czech Republic) calibrated according to Gattacceca et al. [18]. Whenever possible, the magnetic susceptibility was measured along three orthogonal axes to take into account the magnetic anisotropy of ordinary chondrites [19]. Some small samples were measured using a Multifunction Kappabridge MFK1-FA (AGICO, Czech Republic) at KFU. The measurements were carried out at a standard frequency of 976 Hz.

2. Results

The obtained hysteresis loops are of excellent quality (Fig. 1) because H and L chondrites are characterized by a high average content of Fe–Ni minerals (18.2 wt% in fresh H chondrites and 8.45 wt% in fresh L chondrites [10]).

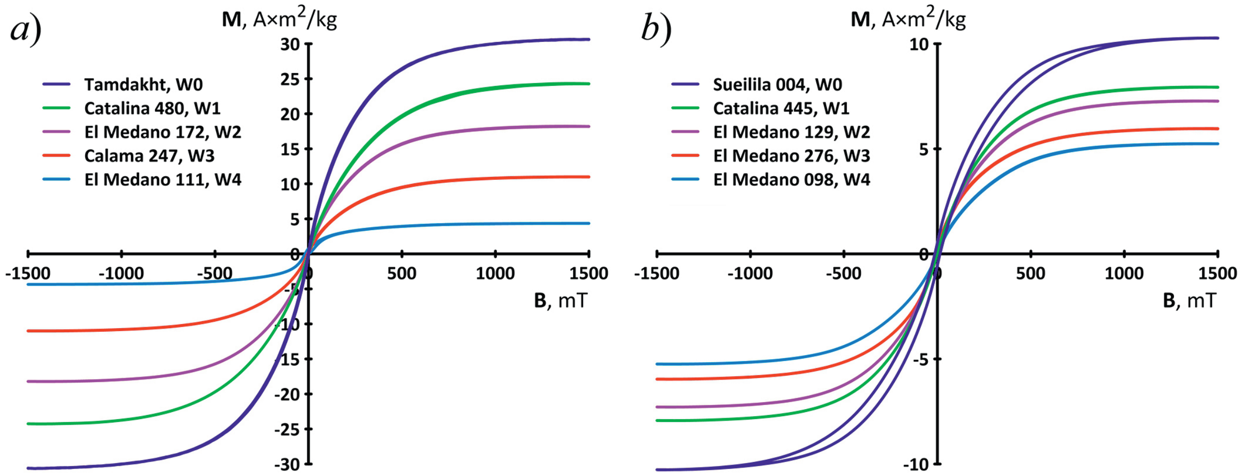

Fig. 1. Hysteresis loops for a) H group W0-1-2-3-4, b) L group W0-1-2-3-4

For 28 meteorites, two different samples were measured at CEREGE (average sample mass 244 mg) and KFU (average sample mass 493 mg). The resulting two sets of measurements show an excellent overall agreement, with the coefficient of correlation (R^2) for linear fits between the M_s, M_{rs}, B_c, and B_{cr} datasets of 0.96, 0.96, 0.93, and 0.94, respectively. The corresponding slopes are 1.06, 0.96, 0.93, and 0.94, thus indicating a proper cross-calibration of the instruments used at both laboratories. However, when considering each pair of samples from individual meteorites, the average deviations from the mean value are 17, 22, 25, and 23 % for M_s, M_{rs}, B_c, and B_{cr}, respectively. They can be attributed to the moderate variations observed in the amount and/or nature of ferromagnetic minerals contained by the samples weighing 200–500 mg and must be considered while interpreting the full dataset. When multiple samples from the same meteorite were measured, the results were combined into a single value (mass-weighted average).

The full hysteresis database is given in Table, which also includes the susceptibility values for the same samples that were used in the hysteresis measurements (average mass 435 mg, median mass 448 mg), as well as for the main mass of the meteorite (average mass 548 g, median mass 171 g).

Table. Magnetic parameters, group, weathering grade, and mass of the studied meteorites (* – collection from Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences. The rest of the meteorites – CEREGE collection)

Meteorite	Group	W	Studied mass, mg	M_s, A×m²/kg	M_{rs}, A×m²/kg	B_c, mT	B_{cr}, mT	χ, m³/kg small piece	χ, m³/kg large piece
1	2	3	4	5	6	7	8	9	10
Calama 027*	H5	3	525	16.02	1.14	9.15	30.10		8.91E-05
Calama 153*	H5	2	186	18.28	0.45	4.09	26.20		9.55E-05
Calama 159*	H5	2	104	31.97	0.36	2.89	78.60		1.20E-04
Calama 247*	H4	3	492	12.31	0.34	4.99	30.20	6.49E-05	8.13E-05
Calama 279*	H5	1	705	28.57	0.24	1.81	90.30	1.63E-04	1.62E-04
Calama 310*	H5	3	168	8.56	0.48	8.88	35.00		6.92E-05
Caleta el Cobre 003	H5	2	222	6.91	0.34	7.48	28.71	3.38E-05	
Caleta el Cobre 020	H5	3	498	0.00	0.87	16.22	41.00	4.22E-05	5.37E-05
Catalina 146	H5	1	448	30.61	0.16	1.38	21.90	1.48E-04	1.35E-04
Catalina 229	H5	1	464	27.82	0.28	2.09	46.90	1.48E-04	1.78E-04
Catalina 474	H5	3	1279	13.00	0.55	9.16	35.20		6.03E-05
Catalina 476	H5	1	922	34.86	0.24	1.27	24.50	1.69E-04	1.70E-04
Catalina 477	H5	1	893	29.13	0.33	2.41	68.30	1.61E-04	1.26E-04
Catalina 478	H5	1	442	32.76	0.31	2.57	24.20	1.43E-04	1.26E-04
Catalina 480	H5	1	1060	25.81	0.13	1.33	24.10	1.45E-04	1.51E-04
Catalina 517	H5	1	862	26.39	0.29	1.92	32.90	1.78E-04	1.58E-04
Catalina 524	H6	3	553	15.68	0.49	4.91	22.20	8.17E-05	1.00E-04
Catalina 535	H5	1	615	20.23	0.21	2.22	57.00	1.20E-04	1.41E-04
Catalina 538	H5	1	757	27.16	0.27	2.24	27.50	1.60E-04	1.55E-04
Catalina 548	H6	1	1083	17.28	0.38	4.95	103.50		1.29E-04
Catalina 555	H5	2	546	14.03	0.26	4.86	42.00	5.10E-05	5.50E-05
Catalina 572	H5	1	594	28.33	0.28	2.19	103.40	2.15E-04	1.62E-04
Chug Chug 002*	H5	1	321	29.37	0.17	1.04	40.90		2.24E-04
Chug Chug 045*	H6	1	147	18.61	0.69	7.05	52.40		1.29E-04
Chug Chug 065*	H5	1	96	22.94	0.36	2.98	59.20		1.55E-04

Table (continued)

1	2	3	4	5	6	7	8	9	10
Chug Chug 067*	H5	1	100	24.63	0.65	4.91	34.50		1.15E-04
Chug Chug 097*	H5	3	876	18.68	0.82	8.95	34.10	1.05E-04	1.17E-04
Chug Chug 146*	H5	2	115	23.32	0.23	1.99	44.90		1.00E-04
El Médano 004	H4	1	290	31.12	0.31	1.85	70.04	1.90E-04	
El Médano 010	H4	4	149	11.26	0.31	5.94	32.21	5.17E-05	
El Médano 011	H6	3	281	12.94	0.31	4.85	35.16	7.37E-05	
El Médano 012	H6	3	230	14.95	0.43	4.54	33.58	1.03E-04	
El Médano 014	H4	2	134	14.20	0.40	4.44	30.59	7.61E-05	
El Médano 021	H6	3	210	9.07	1.00	14.59	34.07	5.17E-05	
El Médano 025	H6	3	621	13.86	0.49	7.15	38.20	7.52E-05	8.13E-05
El Médano 027	H5	3	612	13.19	0.30	5.64	34.80	6.10E-05	8.51E-05
El Médano 030	H6	3	90	13.07	0.26	3.77	35.93	6.62E-05	
El Médano 032	H6	2	449	6.85	0.38	9.03	40.23	5.25E-05	
El Médano 033	H5	4	335	4.43	0.54	14.22	32.61	2.78E-05	
El Médano 036	H5	3	212	6.14	0.76	12.04	24.89	4.56E-05	
El Médano 049	H4	3	398	7.93	0.48	11.36	37.70	3.70E-05	6.46E-05
El Médano 055	H6	2	540	16.27	0.49	5.76	46.30	1.05E-04	1.51E-04
El Médano 071	H5	2	529	28.30	0.51	3.39	36.20	1.58E-04	1.55E-04
El Médano 079	H5	2	450	20.30	0.88	10.88	46.70	8.88E-05	1.35E-04
El Médano 086	H4	1	517	29.49	0.25	1.54	33.90	1.76E-04	1.32E-04
El Médano 092	H6	3	466	9.40	0.68	12.81	44.00	5.68E-05	6.92E-05
El Médano 099	H5	3	466	9.44	0.29	5.84	31.50	5.37E-05	5.37E-05
El Médano 111	H5	4	386	4.45	0.76	18.17	36.50	2.36E-05	2.45E-05
El Médano 115	H5	1	575	34.59	0.19	1.26	24.90	1.63E-04	1.51E-04
El Médano 118	H5	3	452	18.94	0.26	2.70	40.50	1.38E-04	9.77E-05
El Médano 126	H5	3	493	7.52	0.44	10.14	38.90	3.80E-05	7.41E-05
El Médano 172	H5	2	414	18.53	0.25	2.62	30.70	1.05E-04	1.58E-04
El Médano 191	H5	2	530	20.49	0.49	5.66	40.70	9.72E-05	1.12E-04
El Médano 199	H6	1	547	28.79	0.37	2.50	37.50	1.63E-04	1.55E-04
El Médano 231	H4	2	278	27.18	0.34	2.58	141.20	1.93E-04	2.00E-04
El Médano 236	H5	1	494	17.97	0.55	6.59	34.60	8.02E-05	1.55E-04
El Médano 245	H5-6	1	476	27.62	0.29	2.31	105.90	1.34E-04	1.91E-04
El Médano 257	H3	2	540	12.15	0.42	9.32	60.00	4.67E-05	4.90E-05
El Médano 261	H3	2	449	20.91	0.15	2.03	41.40	1.01E-04	8.71E-05
El Médano 278	H5	2	468	9.44	0.24	8.69	78.70	3.78E-05	1.15E-04
El Médano 304	H5	1	438	29.02	0.30	1.93	41.70	1.71E-04	1.86E-04
El Médano 309	H5	3	422	20.81	0.22	2.00	28.90	1.39E-04	8.71E-05
San Juan 011	H4	2	210	16.84	0.31	4.01	33.08	8.41E-05	

Table (continued)

1	2	3	4	5	6	7	8	9	10
San Juan 003	H5	2	188	21.17	0.21	2.10	54.83	1.21E-04	
San Juan 012	H5	2	74	12.66	0.75	7.95	20.33	8.62E-05	
San Juan 020	H5	3	175	14.63	0.59	5.35	18.72	8.99E-05	
San Juan 025	H5	2	193	7.20	0.47	11.43	34.07	4.66E-05	
Sierra Gorda 007*	H5	3	935	19.36	0.42	3.89	25.90		8.91E-05
Sierra Gorda 026*	H4	2	134	26.92	0.24	1.98	15.40		1.20E-04
Sierra Gorda 033*	H5	2	76	29.69	0.33	1.73	65.20		1.70E-04
Calama 003*	L5	2	740	9.68	0.17	3.60	266.40	6.07E-05	4.37E-05
Calama 273*	L6	1	139	6.36	0.15	5.06	106.00		2.04E-05
Caleta el Cobre 006	L6	3	463	3.70	0.14	6.82	35.60	1.97E-05	1.45E-05
Caleta el cobre 009	L4	1	234	6.43	0.13	3.80	36.04	4.57E-05	
Caleta el Cobre 010	L4	1	266	24.48	0.25	2.30	61.27	1.52E-04	
Caleta el Cobre 012	L4	1	238	15.30	0.55	6.77	39.70	7.97E-05	
Caleta el Cobre 015	L6	3	310	3.90	0.12	5.80	36.30	2.10E-05	2.19E-05
Catalina 445	L6	1	641	9.27	0.06	1.65	29.70	4.17E-05	3.98E-05
Catalina 475	L6	2	264	6.28	0.28	13.32	264.30	1.56E-05	2.40E-05
Catalina 479	L6	2	226	4.50	0.22	12.20	82.40		1.82E-05
Catalina 556	L6	2	412	4.70	0.14	6.34	39.40	2.73E-05	4.27E-05
Catalina 562	L6	2	765	9.73	0.09	2.02	27.00	4.07E-05	4.90E-05
Catalina 563	L6	2	494	10.63	0.06	1.37	24.20	5.48E-05	5.25E-05
Chug Chug 011*	L6	1	189	4.05	0.25	14.80	67.30		1.32E-05
Chug Chug 016*	L5	3	340	4.29	0.24	12.50	70.60	1.96E-05	2.00E-05
Chug Chug 066*	L6	2	426	11.50	0.30	4.84	30.20	8.30E-05	4.17E-05
Chug Chug 084*	L6	1	144	8.55	0.20	5.61	31.60		3.98E-05
El Médano 008	L6	3	134	5.65	0.18	8.62	55.00	2.24E-05	
El Médano 016	L6	4	104	1.66	0.14	11.16	25.50	9.31E-06	
El Médano 020	L6	3	187	5.97	0.21	9.83	43.63		1.91E-05
El Médano 021	L5	3	164	9.98	0.06	1.54	27.14	4.54E-05	
El Médano 023	L6	3	631	8.86	0.25	8.89	253.20	3.27E-05	2.34E-05
El Médano 026	L6	3	143	13.51	0.21	3.90	35.32	1.04E-04	
El Médano 029	L5	1	1357	15.45	0.05	0.78	21.87		7.94E-05
El Médano 037	L6	3	320	7.10	0.30	10.65	150.60	3.61E-05	3.47E-05
El Médano 042	L6	3	457	5.23	0.43	15.40	44.90	2.42E-05	2.24E-05
El Médano 070	L6	3	734	10.28	0.24	4.42	83.50	5.26E-05	3.72E-05
El Médano 075	L4	3	1023	9.25	0.24	5.59	120.80	3.85E-05	3.55E-05
El Médano 078	L6	3	312	6.76	0.14	4.86	40.30	3.17E-05	2.95E-05
El Médano 089	L6	4	449	5.96	0.23	7.18	53.90		1.78E-05
El Médano 097	L5-6	3	633	5.53	0.18	6.61	47.40	3.06E-05	2.09E-05
El Médano 098	L6	4	516	5.34	0.09	3.37	42.50	3.55E-05	1.51E-05

End of Table

1	2	3	4	5	6	7	8	9	10
El Médano 113	L6	3	393	5.45	0.21	10.82	232.90	2.19E-05	1.48E-05
El Médano 128	L6	2	474	5.46	0.30	10.27	45.70	2.62E-05	3.55E-05
El Médano 129	L6	2	436	7.41	0.16	5.46	42.60	3.09E-05	3.02E-05
El Médano 135	L6	3	467	6.26	0.37	13.62	47.60	3.35E-05	3.02E-05
El Médano 170	L4	2	556	10.27	0.13	2.40	48.90	3.71E-05	6.31E-05
El Médano 173	L6	2	570	9.77	0.31	7.50	42.90	4.86E-05	4.07E-05
El Médano 253	L6	2	539	9.48	0.10	2.71	34.50		4.47E-05
El Médano 263	L6	3	439	5.12	0.18	8.92	55.80	2.09E-05	2.29E-05
El Médano 276	L6	3	600	6.04	0.33	10.78	43.90	3.35E-05	3.09E-05
El Médano 286	L6	3	536	2.69	0.10	10.49	122.70	9.93E-06	1.82E-05
Sierra Gorda 042*	L6	1	232	10.95	0.12	2.87	30.50		5.01E-05
Sierra Gorda 047*	L5	1	429	7.99	0.24	6.25	43.90	4.62E-05	3.98E-05
Sierra Gorda 088*	L5	1	159	2.94	0.04	3.32	31.20		4.37E-05
Sierra Gorda 090*	L5	2	500	4.51	0.25	13.70	120.80	1.77E-05	2.63E-05
Tamdakht	H5	0	784	30,61	0,24	1.58	74.8		2.00 E-04
Sueilila 004	L6	0	975	10.26	0,54	13,75	399		7.41 E-05

The degree of weathering in ordinary chondrites is traditionally expressed using a scale of weathering grades (from W0 to W6) [20]. The grades are determined in polished meteorite sections from the percentage of oxidized metal and troilite. W1, W2, W3, and W4 correspond to the oxidation of up to 20, 20–60, 60–95, and 95–100 %, respectively. W0 indicates no visible oxidation, but such meteorites are not present in the studied meteorite collection. Similarly, no meteorites with the weathering grades W5 and W6 (weathering of silicates) were found. The weathering grades of the analyzed meteorites are provided in line with the Meteoritical Bulletin Database (https://www.lpi.usra.edu/meteor/) and listed in Table.

3. Discussion

The results presented above were used to quantify the effect of weathering on the magnetic properties of ordinary chondrites. Figs. 3 and 4 show the magnetic parameters M_s, χ, M_{rs}/M_s, and B_{cr}/B_c as a function of the weathering grades in H and L chondrites.

In H chondrites, an increase in the weathering degree is accompanied with a clear decrease of M_s (Fig. 2, *a*). This decrease can be compared to a theoretical trend based on the percentages of oxidized metal in the meteorite, as defined by Wlotzka's weathering scale [20], and assuming that weathered Fe–Ni metal transforms only into paramagnetic minerals (such as akaganeite) or ferromagnetic minerals like goethite that do not add much to magnetism compared to kamacite (M_s = 224 A×m²/kg), the main magnetic mineral of both H and L chondrites (89 and 83 % of the total M_s, respectively) [10]. The M_s and χ values of W0 chondrites were retrieved from Gattacceca et al. [10] and Rochette et al. [9], respectively. The observed decrease is broadly consistent with the theoretical trend (Fig. 2, *a*), which suggests that magnetite or maghemite are present only in minor amounts during weathering. In fact, the formation of magnetite (M_s = 92 A×m²/kg) or maghemite (M_s = 75 A×m²/kg) would move the M_s values above the theoretical trend. This is in good agreement with other studies using Mössbauer spectroscopy and showing that akaganeite (weakly magnetic phase) is the main mineral formed in the early stages of meteorite weathering [21, 22]. Specifically, M_s is slightly below the theoretical trend for W1, which can be interpreted as a fast initial weathering of Fe–Ni metal compared to troilite. Earlier experiments with ordinary chondrites have also shown that Fe–Ni metal tends to weather faster than troilite [23]. In the later stages of weathering, M_s is either at the upper limit of the theoretical value (W3) or slightly above the theoretical trend (W4). This suggests that magnetite and/or maghemite are formed in small amounts during the advanced stages of weathering and has been confirmed by Mössbauer spectroscopy [21]. The above observations and conclusions apply to the changes in magnetic susceptibility of the large meteorite samples with an increase in weathering intensity: overall fit with the theoretical values for transformation of kamacite into non- or weakly magnetic species, fast initial weathering of metal compared to troilite, and formation of magnetite starting from W3 (Fig. 2, *b*). The same trends are also reflected in the magnetic susceptibility measurements of the small meteorite samples (Fig. 2, *c*).

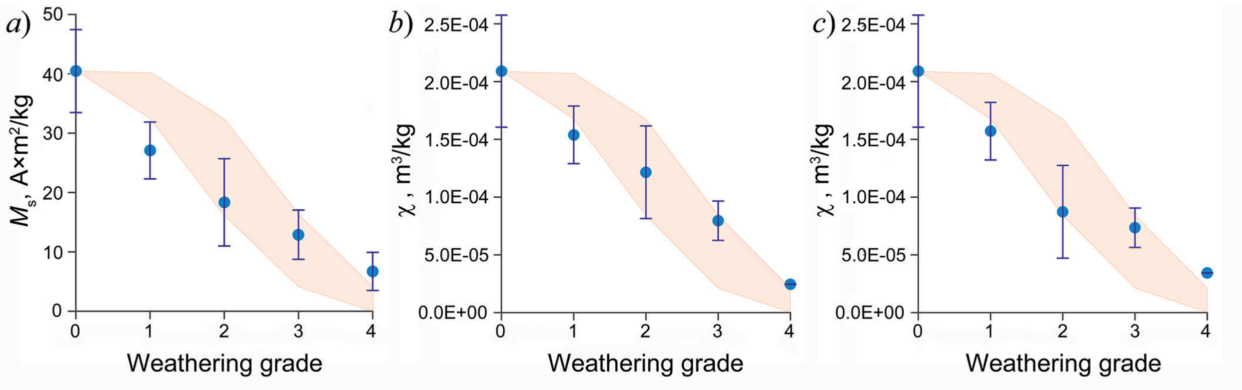

Fig. 2. Magnetic properties of the H chondrites: (*a*) M_s *vs*. weathering grade. Shaded areas indicate the theoretical range if all metal is replaced by paramagnetic minerals; (*b*) Magnetic susceptibility of the large samples *vs*. weathering grade. Shaded area indicates the theoretical range if all metal is replaced by paramagnetic minerals; (*c*) Magnetic susceptibility of the small samples *vs*. weathering grade. Shaded area indicates the theoretical range if all metal is replaced by paramagnetic minerals

Variations were also revealed in the hysteresis parameters, which are not directly linked to the amount of magnetic minerals and rather depend on their nature. The ratios of M_{rs}/M_s and B_{cr}/B_c that are commonly used to investigate the nature of ferromagnetic minerals changed in a consistent way as the meteorite weathered, with an increase of M_{rs}/M_s and a decrease of B_{cr}/B_c (Fig. 3). A similar trend was observed by Uehara et al. using a more limited dataset [12] and can be attributed to the formation of fine-grained goethite and/or magnetite driven by the weathering-induced transformation of Fe–Ni minerals.

The exact same trends hold for L chondrites: M_s and magnetic susceptibility decrease with weathering grade as paramagnetic minerals begin to form, M_{rs}/M_s increases with weathering grade, and B_{cr}/B_c decreases with weathering grade (Figs. 4 and 5).

The magnetic trends in L chondrites are not as strong as in H chondrites because kamacite contributes less to the total M_s in L chondrites (83 %) than in H chondrites (89 %, [10]), and the weathering rate of Ni-rich taenite and tetrataenite is notably slower than that of Ni-poor kamacite. Fig. 5 shows that in L chondrites, just like in H chondrites, the metal begins to weather faster than troilite, and magnetite and/or maghemite formation occurs when the weathering process reaches grade W3.

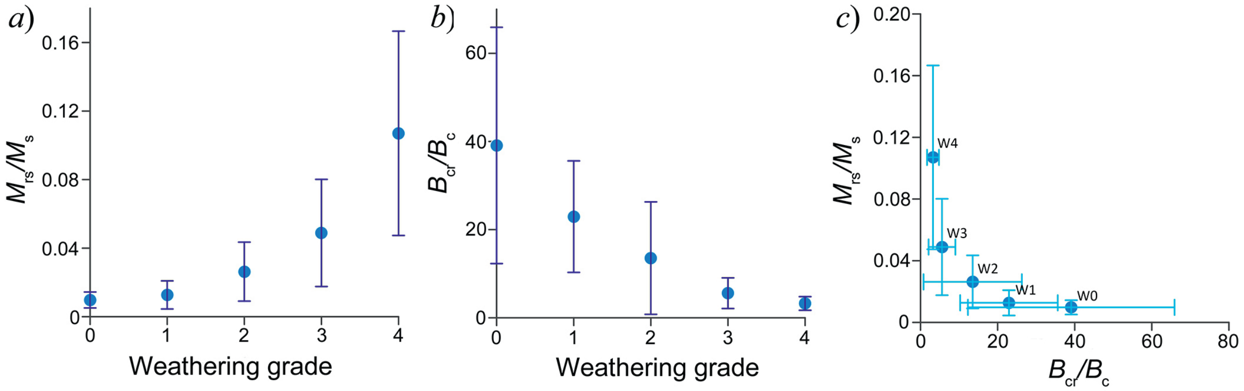

Fig. 3. Hysteresis parameters of the H chondrites: (*a*) M_{rs}/M_s *vs*. weathering grade; (*b*) B_{cr}/B_c *vs*. weathering grade; (*c*) M_{rs}/M_s *vs*. B_{cr}/B_c

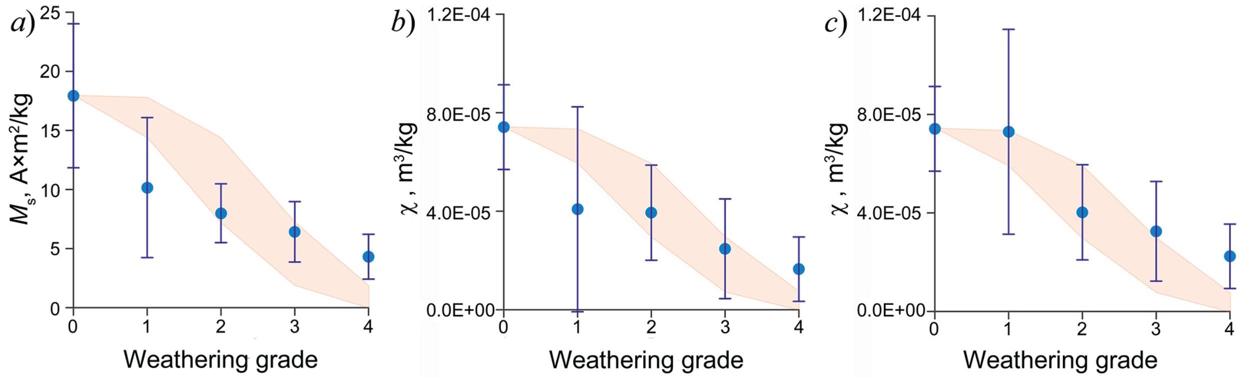

Fig. 4. Magnetic properties of the L chondrites: (*a*) M_s *vs*. weathering grade. Shaded area indicates the theoretical range if all metal is replaced by paramagnetic minerals; (*b*) Susceptibility of the large samples *vs*. weathering grade. Shaded area indicates the theoretical range if all metal is replaced by paramagnetic minerals; (*c*) Susceptibility of the small samples *vs*. weathering grade. Shaded area indicates theoretical range if all metal is replaced by paramagnetic minerals

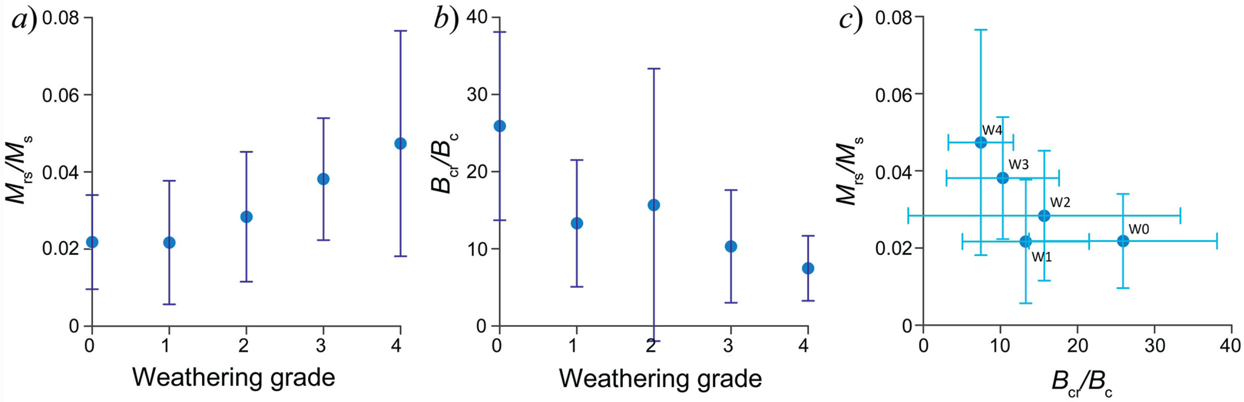

Fig. 5. Hysteresis parameters of the L chondrites: (*a*) M_{rs}/M_s *vs*. weathering grade; (*b*) B_{cr}/B_c *vs*. weathering grade; (*c*) M_{rs}/M_s *vs*. B_{cr}/B_c

Conclusions

Under the effect of terrestrial weathering, the magnetic properties of all H and L ordinary chondrites from this study changed in a predictable way. The saturation magnetization and magnetic susceptibility decreased with an increase of weathering intensity. In the initial stages of weathering, Fe–Ni metal broke down faster than troilite and transformed into mostly paramagnetic iron oxyhydroxides, mainly akaganeite, as indicated by earlier studies using Mössbauer spectroscopy. During the later stages of weathering, small amounts of ferromagnetic minerals with relatively high M_s (magnetite and/or maghemite) were formed, which also aligns with Mössbauer spectroscopy data.

Similarly to magnetic susceptibility, the hysteresis properties of the relatively small H and L ordinary chondrite samples (average mass 435 mg in this study) turned out to be very sensitive proxies to the degree of terrestrial weathering of these meteorites. This is especially true for certain magnetic parameters (M_{rs}/M_s and B_{cr}/B_c) that depend on the mineralogy of magnetic minerals rather than on their concentration. Even at low weathering grades, these parameters changed significantly. Thus, any paleomagnetic study on these meteorites should preferentially focus on meteorites with no signs of weathering, i.e., on fresh meteorite falls.

Conflicts of Interest. The authors declare no conflicts of interest.

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