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Authenticating the recovery location of meteorites: The case of Castenaso

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Abstract–This forensic work aims to authenticate the recovery location of Castenaso, a 120 g ordinary chondritic (L5) meteorite reportedly found in 2003 along the sandy bank of the Idice Stream, near the village of Castenaso (Bologna, Emilia-Romagna, Italy). Using the hypothesis that Castenaso was instead a hot-desert meteorite, we conducted a comparative mineralogical and geochemical study of major weathering effects on European and Saharan ordinary chondrites as potential markers of the environment where Castenaso resided during its terrestrial lifetime.

Inductively coupled plasma-mass spectrometry (ICP-MS) data reveals that Castenaso is significantly enriched in Sr, Ba, Tl, and U, and suggests geochemical alteration in a hot-desert environment. The alteration is minor: Castenaso is not coated by desert varnish and does not show significant light rare earth element (LREE) enrichment or loss of Ni and Co.

The apparent contrast in size, morphology, and composition between the soil particles filling the external fractures of Castenaso and those from the bank of the Idice Stream observed under the scanning electron microscope (SEM) suggests that Castenaso did not reside at the reported find location. Abraded quartz grains (up to 1 mm in size) in Castenaso are undoubtedly from a hot-desert eolian environment: they are well-rounded and show external surfaces characterized by the presence of dish-shaped concavities and upturned silica plates that have been subject to solution-precipitation and subsequent smoothing.

We therefore conclude that Castenaso is one of the many hot-desert ordinary chondrite finds, probably from the Sahara, that is currently available on the market. This forensic work provides the scientific grounds for changing the name of this meteorite.

INTRODUCTION

In this work we discuss the doubtful origin of a 120 g ordinary chondritic (L5) meteorite find known as Castenaso (Russell et al. 2005), along with implications for the weathering effects on ordinary chondrite finds.

Castenaso is currently maintained by the Osservatorio Astronomico e Museo "G. Abetti" in S. Giovanni in Persiceto, Bologna, Italy (OAM), which acquired the specimen from amateur naturalist Franco Merighi. Mr. Merighi reported to Romano Serra, curator of OAM, that he found the stone sitting on the sandy soil of the right bank of the Idice Stream near the village of Castenaso (Bologna, Emilia-Romagna, Italy; 44°29′42″N, 11°21′20″E) on July 15, 2003. Details of the circumstances of the find were published in an Italian popular science magazine on astronomy (Serra 2003). At the request of R. Serra, we classified the meteorite. Based on petrographic observations carried out on three polished thin sections made available by OAM, we classified Castenaso as an L5, slightly weathered (W1), ordinary chondrite. The finding of this new meteorite and its classification was then announced in Meteoritical Bulletin No. 89 (Russell et al. 2005).

Of the thirty-eight official Italian meteorites so far documented since 1792, only six were found, whereas the other thirty-two were witnessed falls (Grady 2000; Meteoritical Bulletin Database at http://tin.er.usgs.gov/ meteor/metbull.php). Castenaso thus appeared to be an extraordinary find, and for this reason we subsequently decided to undertake its full characterization. For this purpose, the complete stone was made available to us by the OAM curator. At first glance, however, the stone looked suspicious to us because it resembled a weathered hot-desert chondrite with a partially oxidized and polished fusion crust (Fig. 1). In addition, further observations under the stereomicroscope revealed that the specimen had been carefully cleaned, with apparent removal of soil from the few fractures present on its external surface. Nevertheless, by



Fig. 1. Macroscopic views of Castenaso. a) Castenaso measures $4.3 \text{ cm} \times 4.0 \text{ cm} \times 2.3 \text{ cm}$ and has a rounded shape. It is covered with an oxidized and polished fusion crust, except on one side, which is characterized by a rust-stained broken surface. Fracturing is minor. The specimen shows clear evidence of thorough cleaning and removal of the loose material filling the cracks. The arrow indicates the fracture where some residual soil was found after upturning. b) A corner was sawed off to produce sub-samples for analysis. The cut surface reveals a relatively fresh gray-green interior, with moderate oxidation of the metal particles.

upturning one deep fracture, we found some residue of the original soil filling the cracks. The remaining soil turned out to be mainly composed of rounded, millimeter-size quartz grains (see below). The morphology of the quartz grains, which is typical of eolian environments, is anomalous for a meteorite found in a fluvial environment. Because of these apparent anomalies, we decided to authenticate its recovery location through a forensic study. We thus analyzed some weathering features of Castenaso as potential markers of the environment where it resided during its terrestrial lifetime. Under the suspicion that Castenaso was actually a meteorite from a hot-desert for the reasons explained above, we focused on three tests that can be performed through relatively fast, routine petrographic and geochemical analyses requiring low sample consumption. The first test consisted of checking for the presence of desert varnish, which is a typical coating of weathered hot desert meteorites (e.g., Lee and Bland 2003). Since weathered ordinary chondrites from hot deserts are typically enriched in Sr and Ba and depleted in Fe, Ni, S, and Co (Stelzner et al. 1999; Al-Kathiri et al. 2005; Gnos et al. 2006), the second test consisted of a comparative geochemical study of Castenaso and several European and Saharan ordinary chondrites finds analyzed ad hoc. The third test consisted of comparing the mineralogy of the fracture material in Castenaso and other Saharan meteorite finds with the soil where Castenaso was reportedly found.

SAMPLES AND ANALYTICAL METHODS

One polished thin section cut through the external surface of Castenaso was investigated under an optical and a microanalytical scanning electron microscope (SEM-EDS) PHILIPS XL 30 to check for the presence of desert varnish.

For the geochemical test, we determined the concentrations of thirty-three elements (Sc, V, Cr, Co, Ni, Cu, Ga, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Tl, Th, and U) by inductively coupled plasma-mass spectrometry (ICP-MS) in Castenaso and eleven ordinary chondrite finds from Europe and the Sahara for comparison (Tables 1 and 2). For a consistent comparison of the geochemical signature imparted by terrestrial weathering to ordinary chondrites in different environments, we chose four meteorites from Europe and four from the Sahara having the same chemical class and similar petrographic type (i.e., L6) as Castenaso (L5). One moderately weathered H5 from the Sahara and one H4 from Europe were also included in the studied set of meteorites to improve the data set, since unweathered H and L chondrites have overlapping concentrations of the elements studied (Ni, Co, and Cr excluded) (Wasson and Kallemeyn 1988). The selected Saharan chondrites cover a wide range of weathering levels, namely from weak to severe (i.e., from W1 to W5, according to Wlotzka 1993), in order to obtain representative information about the range of geochemical alteration due to weathering in the Sahara. Likewise, the European chondrites chosen for this work are representative of the range of weathering degrees attained in European environments, namely from weak to moderate (i.e., from W1 to W3). About 2-10 g of fragments taken from the external portion of each meteorite were finely hand-ground in an agate mortar. Only fragments without any visible soil or alteration crusts were selected to prepare the powders. For Castenaso, we sampled and powdered an \sim 7 g chip from the fresher interior, and an ~40% fusion-crusted fragment (~200 mg) taken from the external portion. For the ICP-MS analyses, about 100 mg of each powder were dissolved in screw-top perfluoroalkoxy (PFA) vessels with a mixture of HF and HNO₃ on a hot plate at ~120 °C. The sample solutions were then spiked with Rh, Re, and Bi as internal standards (20 ng ml⁻¹ in the final

Meteorite	Place of recovery	Date of fall/find	Class	WG ^a	Reference	Sample source ^b
Castenaso	Bologna, Emilia-Romagna, Italy	Found 2003	L5	W1	Russell et al. (2005)	OAM
Saharan choi	ndrites					
DaG 653	Al Jufrah, Libya	Found 1999	H5	W1	Grossman and Zipfel (2001)	MNA-SI
DaG 699	Al Jufrah, Libya	Found 1999	L6	W5	Grossman and Zipfel (2001)	MNA-SI
DaG 728	Al Jufrah, Libya	Found 1999	H5	W2	Grossman and Zipfel (2001)	MNA-SI
DaG 922	Al Jufrah, Libya	Found 2000	L6	W1	Russell et al. (2003)	MNA-SI
DaG 931	Al Jufrah, Libya	Found 2000	L6	W3	Russell et al. (2003)	MNA-SI
HaH 241	Ghadamis, Libya	Found 1997	L6	W3	Grossman (1999)	MNA-SI
European ch	ondrites					
Garraf	Barcelona, Spain	Found 1905	L6	W1	Grady (2000)	VOMC
Kermichel	Vannes, Morbiham, France	Found 1911	L6	nd	Grady (2000)	MNHNP
Mainz	Rheinland-Pfalz, Germany	Found 1850 or 1852	L6	W2/3	Grady (2000)	VOMC
Salla	Lappi, Finland	Found 1963	L6	W1	Grady (2000)	UniPg
Villedieu	Molesme, Cote-d'Or, France	Found 1890	H4	W1-3 ^c	Grady (2000)	MNHNP

Table 1. Meteorites studied in this work.

^aWeathering grade after Wlotzka (1993); the weathering grades of Garraf and Mainz were inferred from their petrographic descriptions given by Keil et al. (1986) and Palme et al. (1983), respectively; the weathering grades of Salla and Villedieu were estimated by us, and M. Gounelle and B. Zanda (personal communication, 2006), respectively.

^bOAM = Osservatorio Astronomico e Museo "Giorgio Abetti," S. Giovanni in Persiceto, Bologna, Italy; MNA-SI = Museo Nazionale dell'Antartide, Siena, Italy; VOMC = Vatican Observatory Meteorite Collection, Vatican City State; MNHNP = Museum National d'Historie Naturelle, Paris, France; UniPg = Dipartimento di Scienze della Terra, Università, Perugia, Italy.

 $^{\circ}$ Note that the overall weathering level of Villedieu is W1, but that of the external chip analyzed in this work was higher corresponding to level W3. nd = not determined.

solutions) and diluted to 50 mL in polypropylene flasks. Milli-Q purified water (18.2 M cm), and HF and HNO₃ subboiled in tetrafluorethylene-perfluorpropylene (FEP) bottles were used in each step of sample preparation. Analyses were performed by external calibration using basaltic geochemical reference samples as composition- and matrix-matching calibration solutions. The high-concentration elements Ni, Cr, and Co were determined in the unknown samples using the Allende standard as calibration solution. The correction procedure included 1) blank subtraction, 2) instrumental drift correction using internal standardization and repeated (every 5 samples) analysis of a drift monitor, and 3) oxide-hydroxide interference correction. Typical limits of detection (Table 2) were calculated as the concentrations corresponding to 3 standard deviation of the blank solutions counts. Five replicate analyses of the Allende meteorite reference sample (USNM 3529, split 20, position 22) were performed along with the unknown samples to check for data quality (Table 2). Element concentrations in the Allende standard and in the unknown samples (Table 3) are at least one order of magnitude higher than the detection limits.

The quartz-grains filling the external fractures of Castenaso and two Saharan ordinary chondrite finds, Dar al Gani (DaG) 653 and Hammada al Hamra (HaH) 241, were extracted under a stereomicroscope for the third test. These grains were mounted on a stub for petrographic observations under the microanalytical SEM-EDS. The same analyses were also conducted on soil particles from the bank of the Idice Stream where Castenaso was reportedly found, which were provided by R. Serra (OAM).

RESULTS

The Desert Varnish Test

Lee and Bland (2003) provide a detailed description of the petrographic characteristics of the desert varnish found on weathered meteorites from hot deserts. The Forrest 009 and Nurina 004 ordinary chondrites from the Nullarbor Plain, Australia, with terrestrial ages of ~6 and ~33 kyr, respectively, are coated by an ~100 μ m thick, finely (on the micrometer scale) laminated deposit dominated by Al, Si, Mn, and Fe with local enrichments in Mn and Ba.

Figure 2 features a representative section through the external surface of Castenaso. No layered weathering deposits are observed here. Castenaso is actually coated with a relatively fresh fusion crust, consisting mainly of skeletal olivine microphenocrysts set in glass plus magnetite dendrites, with minor Fe-oxide/oxyhydroxide veins and pseudomorphs of metal and sulfide globules up to ~100 μ m in size. The fusion crust is in direct contact with the chondritic interior of the specimen. We therefore conclude that Castenaso is devoid of desert varnish, in spite of its polished and oxidized macroscopic appearance (Fig. 1a).

The Bulk Chemistry Test

The bulk trace-element contents of the chondrite meteorites studied in this work are reported in Table 3. Castenaso has a typical L-chondrite trace-element composition (Fig. 3a); however, Sr, Ba, Tl, and U are

Table 2. ICP-MS analytical isotopes, limits of detection, and data for the Allende meteorite reference sample.

	2	Limit of detection ^a	Allende ^b (this work)	Allende (literature)	1
Element	Isotope	$(ng g^{-1})$	$(\mu g g^{-1})$	$(\mu g g^{-1})$	Reference ^c
Sc	45	110	11.7 (0.8)	11	1
V	51	19	93 (3)	92	1
Cr	52	140	3180 (160)	3630	1
Co	59	6.4	576 (11)	600	1
Ni	60	44	12,080 (350)	14,200	1
Cu	63	22	92 (1)	119	1
Ga	71	27	6.2 (0.2)	6	1
Rb	85	8.9	1.17 (0.05)	1.2	1
Sr	86	50	14.4 (0.5)	12	1
Y	89	4.0	2.84 (0.09)	3.1	1
Zr	91	38	6.4 (0.2)	9	1
Nb	93	3.2	0.517 (0.007)	0.620	2
Cs	133	3.4	0.095 (0.003)	0.0857	2
Ba	137	40	4.3 (0.1)	4	1
La	139	3.2	0.49 (0.02)	0.52	1
Ce	140	11	1.23 (0.03)	1.33	1
Pr	141	1.2	0.194 (0.007)	0.21	1
Nd	143	16	0.99 (0.05)	0.99	1
Sm	147	20	0.32 (0.01)	0.34	1
Eu	151	3.5	0.13 (0.02)	0.11	1
Gd	157	5.3	0.39 (0.02)	0.42	1
Tb	159	1.1	0.073 (0.004)	0.081	1
Dy	162	5.2	0.47 (0.02)	0.42	1
Но	165	1.6	0.100 (0.006)	0.10	1
Er	167	5.7	0.291 (0.008)	0.29	1
Tm	169	1.2	0.052 (0.001)	0.0572	2
Yb	172	3.0	0.30 (0.02)	0.30	1
Lu	175	1.1	0.042 (0.003)	0.052	1
Hf	178	2.6	0.188 (0.009)	0.21	1
Та	181	1.2	0.033 (0.003)		
Tl	205	2.4	0.08 (0.01)		
Pb	206, 207, 208	40	0.97 (0.08)	1.39	1
Th	232	2.6	0.058 (0.003)	0.065	2
U	238	1.3	0.017 (0.003)	0.016	2

^aLimit of detection calculated as 3 standard deviation of the blank solutions counts.

^bAverage values of five replicate analyses (Allende USNM 3529, split 20, position 22); in parentheses, the standard deviation.

^cReference values from: 1 = Jarosewich et al. (1987); 2 = Friedrich et al. (2003).

anomalously enriched, whereas Rb, Cs, and Pb are anomalously depleted. The crusted fragment of Castenaso taken from the external portion of the meteorite is more enriched in Sr, Ba, Tl, and U with respect to the interior and is also characterized by slightly higher light rare earth element (LREE) concentrations (Fig. 3a).

A comparison with European and Saharan L-chondrite finds, specifically analyzed for this work, reveals that Castenaso has a significant affinity with the chemically altered Saharan finds (Figs. 3a and 3b). In particular, weathering introduces significant mobilization of Ni, Co, Sr, Cs, Ba, LREE, Tl, Th, and U in Saharan chondrites. Moderately to severely altered Saharan L-chondrite finds (\geq W2) are depleted in the siderophile elements Ni and Co (0.45–0.88 and 0.021–0.043 wt%, respectively). This feature was also observed in H chondrites from the Acfer region by

Stelzner et al. (1999), but we show here that it is not present in the European and slightly weathered (\leq W1) Saharan finds and in Castenaso. Moderately to severely weathered Saharan L-chondrite finds (\geq W2) can be enriched in LREE (La/Sm = 2.1-3.1). A similar LREE enrichment was also observed in weathered H and L chondrites from Oman (Al-Kathiri et al. 2005), in weathered samples of the Tatahouine diogenite (Barrat et al. 1999), and in weathered lunar meteorite finds from Oman and Sahara (Ziegler et al. 2006). In turn, the Castenaso "interior" and other European ordinary chondrite finds show no significant LREE enrichment. Slightly to severely weathered (≥W1) Saharan ordinary chondrite finds are enriched in Sr, Ba, Tl, and U relative to European finds of comparable weathering level and L-chondrite falls (Fig. 3b). The anomalous enrichment in Sr and Ba was reported as a geochemical fingerprint of H-chondrite finds from the Acfer

of the studied meteorites.	
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\mathbf{C}	
, Co,	
Bulk Ni	
Table 3.	

	Castenaso (interior)	Castenaso (external)	Garraf	Kermichel	Mainz	Salla	Villedieu	DaG 699	DaG 728	DaG 922	DaG 931	HaH 241
Sc	8.8	9.6	9.0	9.1	8.2	8.4	8.1	9.6	10.2	10.1	9.1	9.6
>	71	73	68	72	68	72	57	79	83	74	96	77
Cr	0.43	0.40	0.40	0.44	0.41	0.43	0.29	0.39	0.42	0.46	0.41	0.38
Co	0.054	0.059	0.062	0.056	0.058	0.038	0.082	0.043	0.021	0.056	0.039	0.032
Ni	1.34	1.41	1.46	1.30	1.34	1.09	1.80	0.88	0.45	1.41	0.71	0.50
Cu	109	117	108	126	112	103	109	94	75	86	98	91
Ga	5.1	5.4	5.5	5.8	5.6	5.6	6.2	6.1	5.9	6.2	5.9	5.8
Rb	1.43	1.41	2.08	2.92	1.92	2.19	1.31	3.09	2.91	3.08	2.75	2.96
Sr	44	55	15.6	8.0	10.1	10.2	6.9	67	115	16.0	126	56
Y	2.23	2.67	2.27	2.47	2.01	1.91	2.39	2.41	2.32	2.44	2.17	2.39
Zr	5.2	4.8	5.3	5.5	5.3	5.2	4.9	5.7	6.2	5.7	5.6	7.0
Nb	0.394	0.368	0.422	0.444	0.435	0.433	0.378	0.481	0.416	0.465	0.466	0.619
C_S	0.026	0.009	0.014	0.192	0.013	0.007	0.023	0.023	0.013	0.014	0.028	0.054
Ba	34	86	16.0	4.6	5.4	6.2	4.0	170	637	8.2	812	46
La	0.321	0.425	0.391	0.418	0.328	0.275	0.444	0.475	0.529	0.425	0.607	0.864
Ce	0.844	1.210	0.971	1.041	0.838	0.722	1.045	1.180	1.293	1.079	1.505	1.963
Pr	0.129	0.165	0.147	0.153	0.120	0.108	0.162	0.157	0.165	0.151	0.174	0.251
Nd	0.647	0.814	0.699	0.767	0.583	0.547	0.79	0.792	0.803	0.759	0.816	1.097
Sm	0.220	0.278	0.203	0.248	0.186	0.181	0.234	0.229	0.238	0.246	0.254	0.282
Eu	0.077	0.080	0.081	0.074	0.080	0.072	0.071	0.085	0.119	0.084	0.111	0.093
Gd	0.278	0.340	0.284	0.321	0.245	0.238	0.316	0.303	0.295	0.286	0.272	0.332
Тb	0.051	0.063	0.054	0.060	0.051	0.048	0.060	0.052	0.056	0.054	0.051	0.060
Dy	0.345	0.401	0.363	0.392	0.316	0.299	0.388	0.358	0.387	0.379	0.347	0.384
Но	0.079	0.091	0.081	060.0	0.073	0.067	0.083	0.084	0.087	0.088	0.077	0.086
Er	0.227	0.257	0.236	0.246	0.204	0.211	0.241	0.244	0.233	0.248	0.220	0.254
Tm	0.036	0.040	0.037	0.039	0.031	0.033	0.037	0.037	0.038	0.038	0.033	0.039
Yb	0.218	0.247	0.239	0.231	0.207	0.194	0.234	0.229	0.228	0.231	0.217	0.245
Lu	0.034	0.037	0.035	0.036	0.030	0.031	0.035	0.033	0.035	0.038	0.033	0.035
Hf	0.163	0.132	0.169	0.169	0.171	0.153	0.144	0.157	0.182	0.164	0.162	0.196
Та	0.023	0.019	0.026	0.033	0.026	0.024	0.023	0.023	0.023	0.030	0.026	0.036
Π	0.013	0.026	0.009	0.011	0.006	0.008	0.004	0.141	0.039	0.012	0.165	0.061
Pb	0.13	0.22	1.07	1.42	6.2	0.56	5.1	0.31	2.66	1.74	1.45	1.31
Th	0.046	0.047	0.073	0.093	0.061	0.046	0.068	0.064	0.064	0.072	0.075	0.172
U	0.032	0.071	0.031	0.032	0.032	0.018	0.021	0.171	0.148	0.033	1.012	0.101



Fig. 2. a) A backscattered electron image of a section through the external surface of Castenaso. Dotted line marks the boundary between the fusion crust and the interior. The external surface of Castenaso consists of a relatively fresh fusion crust with no evidence of desert varnish. b) Some mineralogical and textural details of the fusion crust.

region by Stelzner et al. (1999) and of H- and L-chondrite finds from Oman by Al-Kathiri et al. (2005).

The distribution of the trace elements Rb and Cs in the analyzed OC is more complicated. Castenaso (both the internal and external portion) and Villedieu are depleted in Rb (1.4 and 1.3 μ g g⁻¹, respectively) (Figs. 3a and 3b), whereas the Cs content varies by a factor of 26, from the anomalously low values of the Castenaso crust (9 ng g⁻¹) and Salla (7 ng g⁻¹), to the high value of Kermichel (192 ng g⁻¹). However, from our set of data, we cannot identify a systematically different mobilization style of Rb and Cs between European and Saharan ordinary chondrite finds, possibly because the enrichment/scavenging of these elements is controlled by more complex factors than those producing the Sr, Ba, Tl, and U anomalies.

The trace elements less mobilized during weathering processes show a very reduced variability within the data set



Fig. 3. The Ni, Co, Cr, and other thirty trace-element concentrations in (a) Castenaso and (b) other Saharan and European ordinary chondrite finds normalized to the average composition of forty-two L5–6 chondrite falls from Friedrich et al. (2004) (Ni, Cr, and Ta from Wasson and Kallemeyn 1988). The grey band represents the 10% deviation from the L-chondrite average composition. Elements are ordered by atomic number from left to right.

(Table 3; Figs. 3a and 3b). Even the most severely altered L chondrites analyzed in this work (DaG 931, DaG 699, and DaG 728) preserve their primary ratios between the most weathering-insensitive trace elements (HREE, Ga, Sc, Zr, Hf, Nb, Y, Cr); thus, these elements can be still profitably used for petrological and diagnostic purposes also in severely altered chondritic material.

The Soil in Fractures Test

Figure 4 shows stereomicroscopic views of the material filling the external fractures of Castenaso and two other ordinary chondrite finds from the Libyan Sahara (DaG 653 and HaH 241), and the sandy soil of the bank of the Idice Stream where Castenaso was reportedly found. The material filling the cracks of Castenaso mainly consists of rounded quartz grains up to 1 mm in size (Fig. 4a). Quartz grains with similar size and morphology are also a major constituent of the soils observed in the fractures of the two chondrites from



Fig. 4. Stereomicrographs of quartz grains filling the fractures of (a) Castenaso, (b) DaG 653, and (c) HaH 241. d) A stereomicrograph of the sandy soil from the bank of the Idice Stream where Castenaso was reportedly found.

the Sahara (Figs. 4b and 4c). The soil from the banks of the Idice Stream, in turn, appears to consist of more fine-grained, polymineralic particles of different colors and shapes (Fig. 4d).

Figure 5 shows secondary electron images of the quartz grains in Castenaso, DaG 653, and HaH 241, and in the soil from the banks of the Idice Stream. Quartz grains in Castenaso are well-rounded and show dish-shaped concavities (Fig. 5a) and upturned silica plates (or cleavage plates) that have been subject to solution-precipitation and subsequent smoothing (Fig. 5b). Such features are diagnostic of prolonged processing in a hot-desert eolian environment (Krinsley and Doornkamp 1973): rounded shapes and the upturned silicate plates are due to wind abrasion; dish-shaped concavities are impact craters due to mechanical chipping during particularly powerful sand storms. Such morphological features are in fact also observed in the quartz grains of the two chondrite finds from the Sahara, DaG 653 and HaH 241 (Figs. 5c and 5d). The soil sample from the bank

of the Idice Stream mainly consists of angular quartz and alkali feldspar particles and of fragments of mica plates typically $<100 \ \mu m$ in size.

Figure 6 shows the major element composition of the solution-precipitation external coating of the quartz grains in Castenaso, DaG 653, and HaH 241. The endmember composition of quartz is shown for comparison. An obvious enrichment in Al, Mg, Fe, Ca and alkalis is observed in DaG 653 and HaH 241. Quartz grains in Castenaso fit the Saharan weathering trend. As shown in Fig. 7, smectite compositions are endmembers of the observed weathering trend: this suggests that submicrometer-size smectites may be a possible constituent of the external coat of the quartz grains in Castenaso, DaG 653, and HaH 241.

DISCUSSION AND CONCLUSIONS

Through the study of weathering effects on European and Saharan ordinary chondrite finds, we identified key features



Fig. 5. Secondary electron images (SEI) of quartz grains filling the fractures of (a, b) Castenaso, (c) DaG 653, and (d) HaH 241. e) An SEI of the sandy soil from the bank of the Idice Stream where Castenaso was reportedly found. f) A detail of a quartz grain from the bank of the Idice Stream. Abbreviations: q = quartz; m = muscovite; a = albite; k = K-feldspar.





Fig. 6. Binary diagrams showing the SEM-EDS major element composition of the external surface of the quartz grains filling the fractures of Castenaso, DaG 653, and HaH 241.

that enabled us to determine the actual recovery location of the Castenaso L5 chondrite.

We observe that Saharan ordinary chondrite finds, even if only slightly weathered (e.g., >W1), are systematically and significantly enriched in Sr (>30 μ g g⁻¹), Ba (>20 μ g g⁻¹), U (>50 ng g⁻¹), and Tl (>20 ng g⁻¹) compared to European finds of comparable weathering level. Furthermore, moderately to severely weathered Saharan ordinary chondrite finds (≥W2) are also depleted in Ni (0.45–0.88 wt%) and Co (0.021–

Fig. 7. Ternary diagrams showing the SEM-EDS major element composition of the external surface of the quartz grains filling the fractures of Castenaso, DaG 653, and HaH 241. The SEM-EDS composition of smectites from Cape Roberts, Antarctica, obtained under the same instrumental conditions (Giorgetti et al. 2006, personal communication), are plotted for comparison.

0.043 wt%) and enriched in LREE with La/Sm > 2.1 relative to European finds.

The important enrichment in Sr (44–55 μ g g⁻¹), Ba (34– 86 μ g g⁻¹), Tl (13–26 ng g⁻¹), and U (32–71 ng g⁻¹) in Castenaso indicates geochemical alteration in a hot-desert environment. Alteration is only minor since Castenaso is not coated by desert varnish and does not show a significant LREE enrichment (La/Sm ~1.5) and loss of Ni (1.34– 1.41 wt%) and Co (0.054–0.059 wt%). The apparent contrast in size, morphology, and composition between the soil particles filling the external fractures of Castenaso and those from the bank of the Idice Stream, near Castenaso, Bologna, indicates that this meteorite did not reside at the reported find location. The abraded quartz grains of Castenaso, their surface texture and composition indicate that this meteorite resided in a hot-desert environment. We therefore strongly suspect that Castenaso is not a new find from Italy, but most likely one of the many ordinary chondrite finds from the Sahara currently available on the market. This forensic work provides the scientific grounds for changing the name of this meteorite. The Italian name "Castenaso" should be discarded and substituted with an appropriate name for meteorites of uncertain origin like the ones from the Nova series.

Because of the relative simplicity of the analytical methods adopted (optical microscopy, electron microscopy and microanalyses of the external surface and of the soil scratched from fractures; geochemistry by ICP-MS) and low sample consumption (<1 g), our work provides a good example of how to authenticate meteorites of doubtful recovery location. This work may be of broader interest because the tremendous expansion of the meteorite market in the last decade has generated a need for tools for authenticating the recovery location of meteorites, which is an important attribute in determining the economic and scientific value of each specimen.

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