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Petrography and mineral chemistry of the Reliegos chondrite

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Abstract–The Reliegos meteorite is an L5 ordinary chondrite. The chondrules are embedded in a fine-grained matrix that predominantly consists of olivine and orthopyroxene, with accessory clinopyroxene, troilite, apatite, and a mesostasis of feldspar composition. The metal phase is predominantly kamacite with subordinate taenite and traces of native Cu. The bulk composition of Reliegos compares well with other L5 chondrites, except for a distinctly lower Cr content. A Cr-rich object has been identified, which shows a concentric mineral and chemical zoning and is composed mainly of chromite and plagioclase, with minor amounts of merrillite and Mg, V-rich ilmenite.

INTRODUCTION

Reliegos is the last recorded meteorite fall in Spain (December 28, 1947) in the town of Reliegos, a province of León (Gómez de Llarena and Rodriguez-Arango 1950). A total of 17.3 kg were recovered, of which 7 fragments are located in different museums (Graham et al. 1985; Grady 2000). The specimen studied in this work (620 g) is located at the Museo Geominero, Instituto Geológico y Minero de España (IGME) in Madrid, and has not been previously studied or recorded in any published catalogue. Previous works were focused on the classification and potential pairing of the specimens, and indicated that the meteorite was an ordinary chondrite L5 (McCoy et al. 1990). In this work, we have carried out a detailed petrographic and mineralogical characterization, revealing an unusual Cr-rich object.

BULK ROCK CHEMISTRY

A sample of 1157 mg of the Reliegos meteorite was used for X-ray fluorescence analyses with a Philips PW-1404 spectrometer. Sulphur was analyzed using an ELTRA-CS-800 IR analyzer and sodium content was determined with a Varian FS-220 atomic absorption spectrometer. Bulk Ni and Co contents were analyzed using a Thermo Jarrell Ash ICAP-61 ICP optical emission spectrometer. The only bulk rock analysis of Reliegos published to date (Gómez de Llarena and Rodriguez-Arango 1950) reports anomalously high contents of Ni (11.05 wt%) and Co (0.30 wt%), and probably denotes the bulk composition of the metal fraction, rather than the bulk meteorite composition. Bulk chemistry results reported in this work (Table 1) fit well within the compositional range of L5 chondrites (Jarosewich 1990) except for chromium, which is substantially lower than the values recorded for this chondrite group so far.

PETROGRAPHY

Two polished thin sections (6203-1 and 6203-2) of the Reliegos meteorite were studied in transmitted and reflected light. The hand specimen of Reliegos displays a fine-grained texture. As shown by the modal analysis, this chondrite contains 7 vol% of disseminated metallic grains. Barred olivine, radial pyroxene, and porphyritic olivine-pyroxene chondrule fragments have been identified, as well as a chromite-plagioclase object (800 × 1000 μm). The chondrules and the matrix display a relatively high degree of recrystallization, which is visible in the polished thin sections. Secondary feldspar is also present. Such textural characteristics allow classification of the Reliegos meteorite as a petrologic type 5, confirming the previous classification (McCoy et al. 1990). Chlorapatite has been identified as isolated and anhedral grains (10–80 μm). Opaque minerals include metallic Fe,Ni, troilite, and chromite. Occasionally, some grains of native Cu with grain sizes generally <30 μm are also present and associated with metal and/or troilite grains. Based on planar fractures and weak mosaicism of some olivine crystals (e.g., Stöffler et al. 1991), Muñoz-

Table 1. Bulk chemical composition of Reliegos in comparison with L5 chondrite compositions (wt%).

	Reliegos	L5 chondrites[a] Average	Minimum	Maximum
SiO_2	40.09	39.89	38.79	41.01
Al_2O_3	2.01	2.30	2.14	2.4
Fe^{tot}	28.70	26.89	21.66	31.64
MnO	0.36	0.33	0.28	0.37
MgO	24.11	24.79	24.28	25.34
CaO	1.95	1.83	1.72	2.01
Na_2O	0.98	0.95	0.81	1.08
K_2O	<0.1	0.10	0.07	0.14
TiO_2	0.12	0.11	0.02	0.14
P_2O_5	0.21	0.23	0.16	0.29
Cr_2O_3	0.06	0.60	0.45	1.57
S	2.23	n.a.[b]	n.a.	n.a.
Ni	1.25	1.25	1.05	1.44
Co	0.05	0.07	0.05	0.08

[a]Jarosewich (1990).
[b]n.a. = not analyzed

Espadas et al. (2002) classified the Reliegos meteorite as a shocked S4. Although such features have not been clearly identified in any of the sections studied, the presence of Cr-rich objects and metallic Cu could point to a shocked chondrite (Rubin et al. 2001).

The chromite-plagioclase object displays a microstructure consisting of three clearly identifiable zones (Fig. 1): an outer zone formed by euhedral grains of chromite (1–20 µm) and accessory troilite + Fe, Ni phases (5–30 µm); an intermediate zone consisting of euhedral grains of chromite (1–10 µm) and accessory anhedral merrillite (10–70 µm); and an inner zone consisting of euhedral grains of chromite (1–5 µm) with accessory anhedral illmenite (1–5 µm). All zones are embedded in a mesostasis of plagioclase composition.

MINERAL CHEMISTRY

Mineral analyses were carried out using a JEOL Superprobe JXA-8900M microprobe operated at 20 keV and 15 keV for metallic and silicate minerals, respectively; a beam spot of approximately 20 µm in diameter was used for point analyses of large enough mineral grains, except for chromite, where a 1 µm spot was used due to the fine-grained nature of this mineral in the studied samples. Natural and synthetic silicates, oxides, and metals were used as reference standards. Results of mean chemical compositions and calculated structural formulae of matrix chromite, silicates, and apatite are listed in Table 2.

The microprobe analyses reveal that olivine, orthopyroxene, clinopyroxene, plagioclase, and chromite from chondrules and matrix are homogeneous in composition. Olivines range in composition from $Fa_{22.2}$ to Fa_{24} ($\sigma = 0.44$), and no systematic differences between grains in different patches of the matrix or between matrix grains and chondrules are recognized. The Mn contents range between 0.35 and 0.57 wt%, and the Ca contents never exceed 0.09 wt%. Orthopyroxene compositions are $Wo_{1.3}$ and $Fs_{18.8}$ to $Fs_{20.2}$ ($\sigma = 0.37$), with minor contents of TiO_2, Al_2O_3, Cr_2O_3, MnO, and CaO (Table 2). The few measurable clinopyroxene grains show a diopside composition with $Fs_{5.8–7.3}$. The microprobe analyses of matrix plagioclase display a composition of $An_{14.2–24.9}Ab_{69.0–79.9}Or_{4.5–7.1}$. The analyzed chromite crystals show a composition close to stoichiometry $FeCr_2O_4$, with Fe^{2+} (<3 wt% FeO) partially substituted by Mg and Mn, about 6 wt% Al_2O_3, and appreciable amounts of TiO_2 (3 wt%) and V_2O_3 (0.75 wt%). Fluorine and chlorine contents of apatite range between 0.39–1.00 and 4.26–5.06 wt%, respectively. Compositions of sulphide and metallic phases are summarized in Table 3. Troilite has a virtually stoichiometric composition, with noticeable amounts of Ni (0.18 wt%). Kamacite displays a Ni content from 6.56 to 6.64 wt% and taenite from 29.8 to 32.2 wt%. Co contents in kamacite (0.84–0.88 wt%) are noticeable. Native Cu contains 6.38 wt% Fe, 2.28 wt% Ni, and 0.23 wt% S, probably due to contamination with the Fe, Ni, and troilite host.

Composition of mineral phases in the Cr-rich chondrule are summarized in Table 4. Plagioclase (mesostasis) and chromite from the intermediate and outer zones, merrillite from intermediate zone, and ilmenite from the inner zone have been measured. From rim to core of the intermediate zone, plagioclase compositions are indicative of an igneous zoning (Krot et al. 1993) (A–A′; Fig. 1): SiO_2 and Na_2O contents decrease, while Al_2O_3 and CaO increase from A ($Or_{4.9}Ab_{75.4}An_{19.7}$) to A′ ($Or_{0.6}Ab_{36.1}An_{63.3}$). Chromite compositions also show the same zoning pattern as plagioclase. The Cr/(Cr + Al) ratio decreases from rim (0.85) to core (0.35) as well as the $Fe^{2+}/(Fe^{2+}+Mg)$ ratio, from B (0.88) to B′ (0.60). Small, colorless grains of merrillite occur as elongated anhedral grains in the intermediate zone. The

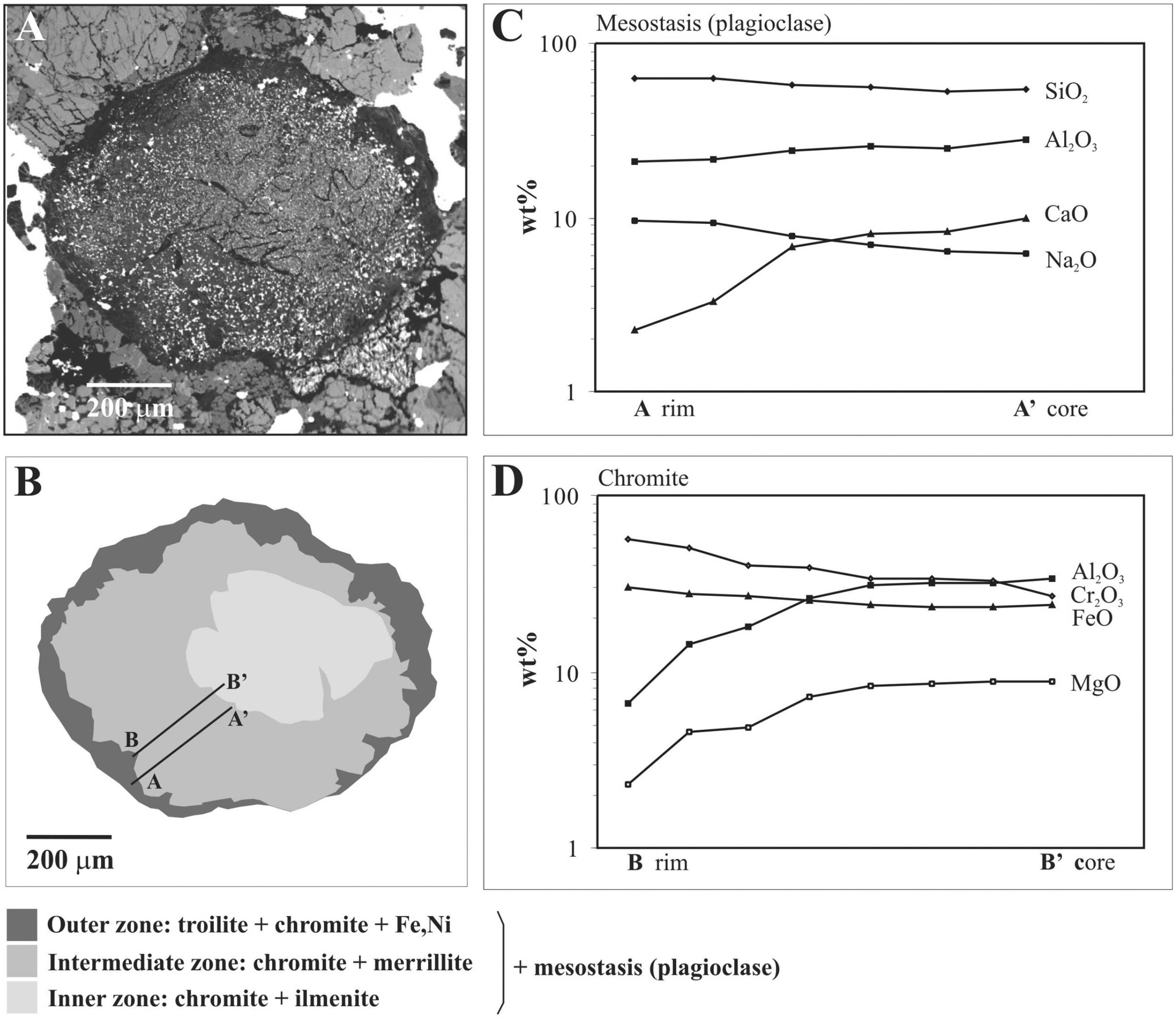

Fig. 1. Mineralogical and chemical zoning of the Cr-rich chondrule: a) backscattered image of the Cr-rich chondrule; b) schematical map showing the three zones defined and the microprobe profiles carried out: A-A′ in plagioclase and B-B′ in chromite; c) microprobe analyses in plagioclase grains from rim to core of the intermediate zone (A-A′); and d) microprobe analyses in chromite grains from rim to core of the intermediate zone (B-B′).

microprobe analyses normalized to the ^{56}O structural formulae, yield a composition close to the theoretical formula $Ca_{18}(Mg,Fe)_2Na_2(PO_4)_{14}$ given by Dowty (1976) for meteoritic merrillites. The $Mg/(Mg+Fe^{2+})$ ratio (0.94) is in the range recorded for merrillites in L chondrites (0.85–0.95) (Kleinschrot 1997). Ilmenite grains contain minor contents of Mg and Mn (5.0 and 1.0 wt%, respectively), similar to ilmenites measured by Krot et al. (1993) in Cr-rich chondrules. In this work, measured V_2O_3 in ilmenites range from 0.82 to 0.99 wt%.

SUMMARY AND CONCLUSIONS

The specimen from the Museo Geominero has not been previously studied or recorded in any published catalog and represents the second largest specimen of Reliegos. Previous works were focused on the classification and potential pairing of the specimens in the MNCN collection (Casanova et al. 1987; McCoy et al. 1990). Textural features and the microprobe analyses of the studied fragment confirm the previous classification as an L5 chondrite.

The detailed mineralogical and petrography study carried out during this work shows an unusual Cr-rich chondrule. The presence of Cr-rich objects is an uncommon event in L and LL chondrites but is relatively common in H chondrites. In fact, only 12% of the L chondrites display Cr-rich objects (Krot et al. 1993). Brearley et al. (1991) defined a Cr-rich inclusion in the Los Martínez (L6) chondrite as consisting of

Table 2. Mean electron microprobe analyses (wt%) of non-metallic phases (except minerals from the Cr-rich chondrule).

	Chromite	Olivine	Orthopyroxene	Clinopyroxene	Plagioclase	Apatite
n	11	39	20	10	18	9
SiO_2	0.03	38.35	55.96	53.30	65.69	0.04
Al_2O_3	5.99	0.08	0.40	0.91	21.45	0.02
FeO	30.31	21.43	13.02	4.51	0.43	0.22
MnO	0.79	0.46	0.47	0.24	0.02	0.03
MgO	2.56	39.51	29.37	17.15	0.30	0.02
CaO	0.02	0.04	0.68	22.17	2.54	52.87
Na_2O	b.d.[a]	0.04	0.05	0.68	9.15	0.38
K_2O	b.d.	b.d.	b.d.	0.03	1.04	b.d.
TiO_2	3.08	b.d.	0.19	0.46	0.05	0.03
Cr_2O_3	56.38	0.10	0.10	0.76	0.05	0.04
P_2O_5	0.02	0.02	0.02	0.05	b.d.	40.95
ZnO	0.33	0.02	–	b.d.	0.03	0.04
V_2O_3	0.75	n.a.[b]	n.a.	n.a.	n.a.	n.a.
F	n.a.	n.a.	n.a.	n.a.	n.a.	0.68
Cl	n.a.	n.a.	n.a.	n.a.	n.a.	4.61
Total	100.31	100.13	100.29	100.33	100.77	99.96
Oxygens	4	4	6	6	8	25
Si	–	1.00	1.99	1.95	2.87	0.01
Ti	0.08	–	0.01	0.01	–	–
Al	0.25	–	0.02	0.04	1.11	–
Fe^{2+}	0.90	0.47	0.39	0.14	0.02	0.03
Mn	0.02	0.01	0.01	0.01	–	–
Mg	0.14	1.53	1.56	0.94	0.02	0.01
Ca	–	–	0.03	0.87	0.12	9.51
Na	–	–	–	0.05	0.78	0.13
Cr	1.58	–	–	–	–	–
Zn	0.01	–	–	–	–	–
V	0.02	–	–	–	–	–
P	–	–	–	–	–	5.82
Cl	–	–	–	–	–	1.31
F	–	–	–	–	–	0.36
Total	3.00	3.01	4.01	4.01	4.92	17.18
			$Fa_{22.2–24}$	$Fs_{18.8–20.2}$ $Wo_{1.3}$	$Or_{4.5–7.1}$ $Ab_{69.0–9.9}$ $An_{14.2–24.9}$	

[a]n.a. = not analyzed.
[b]b.d. = below detection.

Table 3. Mean electron microprobe analyses (wt%) of metallic phases and native Cu.

	Troilite	Kamacite	Taenite	Copper
n	17	26	8	1
Fe	61.86	92.10	68.73	6.38
S	36.92	b.d.	b.d.	0.23
Co	0.07	0.86	0.31	0.02
Ni	0.18	6.60	31.11	2.28
Cu	b.d.	b.d.	b.d.	93.57
Sum	99.03	99.56	100.15	102.48

stoichiometric plagioclase intergrown with a Cr-rich spinel. Crystallographically oriented spinel with respect to the host phase and coarse-grained spinel crystals grown along fractures have been related to exsolution processes in the Los Martínez chondrite (Brearley et al. 1991). These features have not been observed in the Cr-rich chondrules of Reliegos.

As observed in the Reliegos fragment, the compositional zoning of chromite and plagioclase from Cr-rich objects is characterized by an increase in the Cr/(Cr+Al) ratio and the albite contents from core to rim (Brearley et al. 1991; McCoy et al. 1991; Krot et al. 1991; Krot and Ivanova 1992). The structural and chemical zoning of Cr-rich objects may be due

Table 4. Representative electron microprobe analyses (wt%) of mineral phases from the Cr-rich condrule.

	Plagioclase	Plagioclase	Chromite	Chromite	Ilmenite	Merrillite
Position	A	A′	B	B′	–	–
SiO_2	63.56	52.82	0.11	2.92	3.23	b.d.[a]
Al_2O_3	21.02	27.30	6.70	33.85	1.80	b.d.
FeO	0.73	2.04	29.70	24.06	36.23	0.39
MnO	b.d.	b.d.	0.78	0.39	0.96	0.07
MgO	b.d.	0.14	2.31	8.83	5.02	3.55
CaO	2.27	10.45	0.10	0.65	0.82	45.55
Na_2O	9.61	5.74	b.d.	0.29	0.62	2.85
K_2O	0.96	0.16	b.d.	b.d.	0.04	0.08
TiO_2	b.d.	0.08	1.33	0.30	50.02	b.d.
Cr_2O_3	b.d.	0.47	56.97	27.17	0.69	0.14
P_2O_5	b.d.	b.d.	b.d.	b.d.	b.d.	46.73
ZnO	0.09	b.d.	0.46	0.38	b.d.	b.d.
V_2O_3	b.d.	b.d.	0.77	0.09	0.88	b.d.
F	n.a.[b]	n.a.	b.d.	b.d.	0.14	0.41
Cl	n.a.	n.a.	b.d.	b.d.	b.d.	b.d.
Total	98.37	99.45	99.22	99.06	100.48	99.91
Oxygens	8	8	4	4	3	56
Si	2.86	2.41	–	0.09	0.15	–
Ti	–	–	0.04	0.01	1.80	–
Al	1.11	1.47	0.29	1.20	0.08	–
Fe^{2+}	0.03	0.08	0.88	0.60	0.72	0.12
Mn	–	–	0.02	0.01	0.02	0.02
Mg	–	0.01	0.12	0.40	0.18	1.91
Ca	0.11	0.51	–	0.02	0.02	17.43
Na	0.84	0.51	–	0.02	–	1.97
K	0.06	0.01	–	–	–	–
Cr	–	0.02	1.61	0.64	0.02	–
Zn	–	–	0.01	0.01	–	–
V	–	–	0.02	–	0.03	–
P	–	–	–	–	–	14.12
Cl	–	–	–	–	–	–
F	–	–	–	–	–	0.46
Total	5.01	5.02	2.99	3.00	3.02	36.03
	$Or_{4.9}Ab_{75.4}An_{19.7}$	$Or_{0.6}Ab_{36.1}An_{63.3}$				

[a]b.d. = below detection.
[b]n.a. = not analyzed.

to: a) diffusion during parent body metamorphism (Wlotzka 1985; Brearley et al. 1991); b) diffusion during impact heating on the surface of a metamorphosed parent body (Krot and Rubin 1993; Rubin et al. 2001); and c) fractional crystallization from a Cr- and Al-rich melt in a possibly oxidized nebular scenario (McCoy et al. 1991; Krot et al. 1993). Objects formed by processes (a) and (b) display spinel crystals with a clear exsolution pattern in plagioclase (Brearley et al. 1991). In the Reliegos Cr-rich chondrule, spinel does not display any orientation, and the compositional zoning seems best interpreted as igneous crystallization from a Cr- and Al-rich melt in an oxidized nebular scenario.

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