The Getafe rock: Fall, composition and cosmic ray records of an unusual ultrarefractory scoriaceous material[(·)]

J. Martínez-Frías[*], A. Weigel[**], K. Marti[**], T. Boyd[***],
G. H. Wilson[****] and T. Jull[*****]

Abstract

In 1994 a moving car and its driver, on a highway in southern Madrid (Getafe), were struck by a falling rock. Eighty-one additional fragments (total weight : 55.926 kg) were later recovered, which all pointed towards a meteorite fall. A study of the composition of this object revealed an ultrarefractory material displaying a most unusual chemical make-up which differs from any known meteorite class, and for some elements and minerals approaches the composition of CAI (Ca-Al-rich inclusions in chondrites). A study of some cosmic-ray-produced stable and radioactive nuclides indicates: a) space and terrestrial exposure ages which do not exceed 1,000 and 520,000 years, respectively; b) the presence of a small ^{22}Ne excess (1,100 °C fraction), which suggests either a nucleogenic contribution from the ^{19}F$(\alpha,n)^{22}$Ne reaction or a trapped Ne signature distinct from atmospheric Ne, and c) the existence of minor variations in the ^{38}Ar/^{36}Ar ratios also indicating a nucleogenic component or fractionation effects. ^{14}C data are consistent with "modern" carbon originated in the period 1955-1958 and not earlier or more recently. The possibility that the Getafe rock could have a man-made origin (i.e. ceramic and refractory tiles, industrial slag) is also considered.

Keywords:

Getafe rock. Fall. Composition. Cosmic ray records. Meteorite. Slag. Madrid. Spain.

La roca de Getafe: Caída, composición y registro de rayos cósmicos de un material inusual ultrarrefractario de escoria

Resumen

En 1994, una roca impactó, en trayectoria descendente, contra un coche que circulaba por la zona sur de Madrid (Getafe), dañando al conductor en el proceso de caída. Posteriormente, se recuperaron otros ochenta y un fragmentos adicionales, con un peso total de 55.926 kg, apuntando todo ello a que se trataba de una típica caída meteorítica. El estudio mineralógico y geoquímico de la roca de Getafe revela que se trata de un material ultrarrefractario, que muestra una composición muy inusual que difiere de los meteoritos conocidos y que, para algunos elementos y minerales, se aproxima a la composición de las CAI (inclusiones ricas en Ca-Al en condritas). El estudio de algunos núclidos estables y radiactivos producidos por los rayos cósmicos indica: a) edades de exposición en el espacio y terrestres que no sobrepasan los 1.000 y 520.000 años, respectivamente; b) la presencia de un pequeño exceso de ^{22}Ne (fracción a 1.100 °C); esto sugiere, o bien una contribución nucleogénica a partir de la reacción ^{19}F$(\alpha,n)^{22}$Ne, o una signatura de Ne distinta del Ne atmosférico, y c) la existencia de pequeñas variaciones en las relaciones ^{38}Ar/^{36}Ar, hecho que indica también una componente nucleogénica o efectos de fraccionación. Los datos de ^{14}C son consistentes con carbón "moderno" originado en un período muy limitado, entre 1955 y 1958. La posibilidad de que la roca de Getafe pudiera tener un origen artificial (por ej. materiales cerámicos, refractarios, escorias industriales) también se tiene en cuenta.

Keywords:

Roca de Getafe. Caída. Composición. Registro de rayos cósmicos. Meteorito. Escoria. Madrid. España.

1. FALL OF THE GETAFE ROCK (GR)

On 21st June, 1994, at approximately 12 noon, a 1.417 kg object struck a car travelling south from Madrid to Andalucía, in the city of Getafe. The fall was picked up by the Spanish media and by the BBC, the European, and Sky and Telescope and was identified as a probable meteorite. The Getafe rock (GR) was handed over to the "Museo Nacional de Ciencias Naturales" in Madrid on the 22nd June 1994 and was included in the Museum's collection on July 5 under the heading *rock of possible meteoritic origin from Getafe* (Ref #: GET94-001).

The car was hit at about km 17 of the N-IV dual carriageway in an open area without bridges or elevations. The driver stated that the traffic was light and there were no vehicles near him at the time. The circumstances of the fall are documented: by a) mapping of the area and evaluation of trajectory; b) the damage to the car was examined the next day; and c) the driver's report of the accident[1, 2]. The object punched a hole through the windscreen of a car travelling approximately 100 km/h, injuring the driver. The windshield penetration had the shape of the rock and left a whitish ring (approx. 2 cm wide) and a circular halo (approx. 25 cm) of cracks surrounded the hole. The investigations carried out in the Instituto de Cerámica y Vidrio in Madrid revealed that the ring was due to microbrecciation without melting. The projectile bounced off the dashboard, leaving an irregular dent (3 cm wide and 0.5 cm deep), hit and deformed the steel steering wheel (and the driver's right hand), bounced upward, at an angle of ≈20° and a distance of ≈90 cm, bounced off the ceiling after 43 cm (damaging the upholstery), then collided with and broke the rear shelf of the car and, bouncing back, finally dropped on the floor behind the front seats. Along with the large specimen, four tiny fragments (0.2773, 0.1524, 0.0634 and 0.0273 g) were found, the largest of which measures 0.7 × 0.3 × 0.1 cm. Eighty more fragments (weighing from a few grams to more than 5 kg), were later collected in the impact area. The substratum of the Getafe area is made up of sedimentary rocks: marls, gypsum beds and claystones. The total weight of all the fragments is 55.926 kg. All investigations in this report were carried out on the 1.417 kg Getafe "fall" (GR).

2. MINERALOGY, COMPOSITION

The GR is a semi-oriented specimen (apex angle »75°), with an external scoriaceous texture (Fig.1) which resembles either an industrial slag or the

Figure 1. Getafe rock. Note its semi-oriented shape and its scoriaceous texture.

Figura 1. Roca de Getafe. Nótese su morfología semi-orientada y su textura escoriácea.

highly vesicular "scoriaceous-type" micrometeorites (e.g. AM10 and M4) which were recovered in Antarctica[3] . No fusion crust was observed, although textural and colour differences exist between surface (melting patina) and interior. At least two different systems of friction striae as well as two types (milky and dark) of droplet-globules (100-500 mm) were found scattered on its surface. Some of these show presence of impact microcraters and friction striae (Figs. 2 and 3).

Minerals were identified by XRD (X-Ray Diffraction), transmitted and reflected light microscopy, SEM (Scanning Electron Microscopy), and electron microprobe. The GR is made up of a fine grained matrix rich in silicates (mainly larnite and melilite, of gehlenite type) and oxides (mainly wustite and chromite) and inclusions of native iron metal (Fig.4). Minor grains displaying spinel and perovskite compositions (closely associated with melilite as a dark, apparently glassy ground mass), and minute grains of troilite, corundum, and native copper were
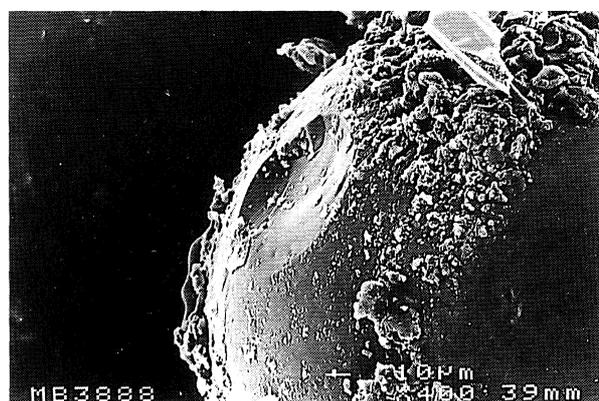
Figure 2. Milky droplet-globule displaying an impact microcrater.

Figura 2. Esfera lechosas mostrando un microcráter de impacto.
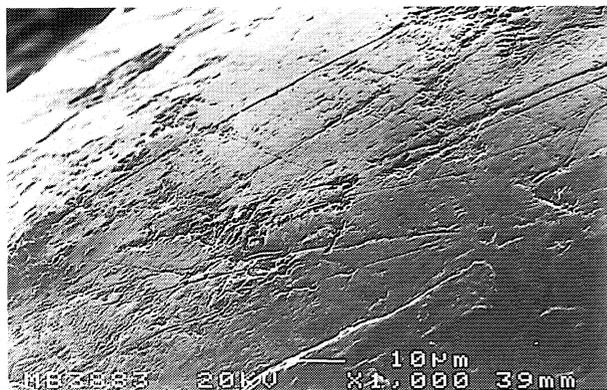
Figure 3. Dark glass droplet-globule showing at least two systems of friction striae.

Figura 3. Esfera oscura mostrando, al menos, dos sistemas de estrías de fricción.

also detected within the matrix. Figure 5 displays the main mineralogical associations of the GR. Although it is difficult to establish a clear crystallization sequence, ore textures seem to reflect a combination of several processes which include: rapid cooling and rapid growth (quenching) from a liquid (as indicated by the presence of acicular, dendritic and spherulitic textures), varying proportions of melted and crystallized zones and some recrystallization.

Apart from the individual textural characteristics of the different mineral phases which will be described below, the most peculiar texture of the GR involves chromite (or chromite-melilite) cores and flower-type wustite rims (Fig.6), and closely resembles the textures detected in the 418/8 Ca-Al-rich inclusion (CAI) from the carbonaceous chondrite Acfer 182[4].

Specific PIXE (Particle-Induced X-Ray Emission) probe analyses were also carried out on 18 spots (6 on iron, 2 metaloxide (wustite) blebs, 7 melilites and 3 larnites). The PIXE data show that PGE and
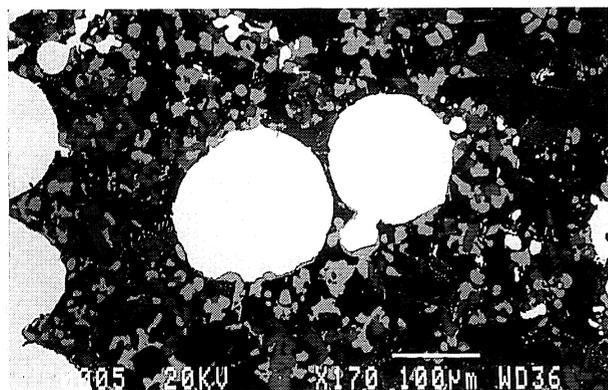
Figure 4: Blebs of native iron which are included in the fine grained matrix rich in silicates.

Figura 4. Gotas de hierro nativo incluidas en la matriz de grano fino rica en silicatos.
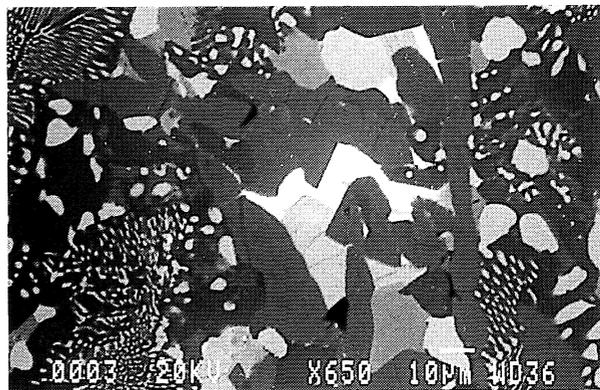
Figure 5. Textural relations between the different mineral phases which form part of the matrix. Troilite (bright white), wustite (white), chromite (light grey), spinel and perovskite association (dark grey).

Figura 5. Relaciones texturales entre las distintas fases minerales que forman parte de la matriz. Troilita (blanco brillante), wustita (blanco), cromita (gris claro), asociación perovskita-espinela (gris oscuro).

the rare earth elements (REE), are below detection limits (detection limits for Re, Os, Ir, Pt and Au are 2040 ppm, and for La are 30 ppm in larnite, 80 ppm in melilite). Calcium olivine (larnite) is a mineral phase which is not found in meteorites. Yoneda *et al.*[5] consider Ca_2SiO_4(larnite), Ca_2SiO_4(alpha) and Ca_2SiO_4(Ca-olivine) as probable condensed mineral species from cosmic gases. Rare terrestrial magmatic occurrences exist which display larnite in a similar paragenesis to that of the GR. Several reactions have been postulated for the origin of larnite. A genetic relationship between larnite and monticellite was suggested in a study of the composition of primary melt inclusions in apatite and monticellite in Magnet Cove carbonatite (Arkansas, USA)[6]. The molten carbonatite crystallized to form daughter phases which include, among others, larnite.
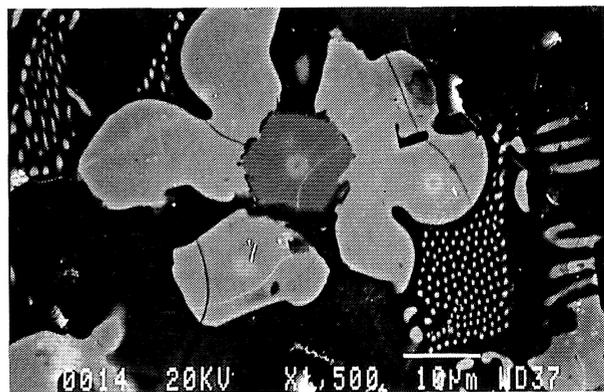
Figure 6. Unusual "flower-type" texture made up by cores of chromite and "petals" of wustite.

Figura 6. Textura inusual de tipo "flor" constituida por núcleos de cromita y "pétalos" de wustita.

Major, minor and trace elements (including REE) of the GR were determined by NAA (Neutron Activation Analysis), ICP-MS, ICP-AES, XRF and AAS (Atomic Absorption Spectrometry). The bulk geochemical composition is rich in iron and calcium (Fe = 18,57 % and Ca = 24,86 %), (reflecting the mineral phases given above), Si (7,60 %), Al (5,68 %), Mn (4,41 %), Mg (2,03 %), Cr (0,97 %) and Ti (0,34 %).

The refractory trace elements Zr, Nb, Sr and Ba are extremely high (20 × CI - 800 x CI) and Y, Ti and V are ≤ 10 × CI; Sc is low (0,2 × CI), and the light REE (La, Ce) are 40 × CI, while the heavy REE are less enriched (approx. 10 × CI). The Ni content is 18 ppm. Its chondrite-normalized REE distribution pattern indicates strong fractionation from LREE (Light Rare Earths) to HREE (Heavy Rare Earths). The oxygen data plot on the terrestrial fractionation line. Two whole rock analyses give $\delta^{18}O$ values of +16.3 % and +15.6 %, and $\delta^{17}O$ values of 8.1 % and 8.0 % (rel. To SMOW (Standard Mid-Ocean Water), which are rather high.

3. COSMIC RAY RECORDS

Cosmic-ray produced nuclides are excellent tracers for the exposure of rocks in space[7]. As the cosmic ray flux at the location (~40° geomagnetic latitude, ~650 m above sea level) of Getafe is about three orders of magnitude lower than in interplanetary space, cosmic ray produced nuclides are expected to answer the question whether space exposure did occur. A pilot study showed essentially terrestrial atmospheric composition for the light noble gases with slight excesses of ^{21}Ne and ^{40}Ar. Therefore, a detailed study of a 388 mg sample of bulk material for all noble gas isotopic abundances was conducted using techniques developed for the study of surface exposure times of terrestrial rocks[8].

Noble gases were released by stepwise heating the sample in a resistance-heated tantalum crucible. The evolved gases were cleaned on a titanium sponge getter and a SAES NP-10 and separated cryogenically. Xenon, krypton, and argon were adsorbed on a stainless steel frit at 77 K and neon and helium were adsorbed on charcoal at 35 and 11 K, respectively. All gases were analysed sequentially by static mass spectrometry using Daly and Faraday detectors on a customized VG5400. Air standards were used for calibration of sensitivities and mass discrimination. An aluminum foil was analyzed for background correction using the same procedures as for the sample.

Noble gas isotopic abundances of the Getafe rock are compiled in table I. Abundances are blank corrected, isotopic ratios are not. Uncertainties represent 68 % confidence level (1σ). Krypton and xenon are consistent with atmospheric abundances and are not given. Neon isotopic ratios of all temperature steps are (within 2.3σ) equivalent to air except for the $^{22}Ne/^{20}Ne$ in the 1,100 °C fraction that is higher. The slight ^{21}Ne-excess, $(2.12 \pm 0.81) \cdot 10^6$ atoms/g, can be used to obtain only an upper limit for the space exposure time of the rock, since some excess may also be due to the $^{18}O(\alpha,n)^{21}Ne$ reaction. With this assumption and using average ^{21}Ne-production rates for space

Table I: Neon and argon isotopic abundances in the Getafe rock (Abundances in million atoms/g)

Tabla I: Abundancias isotópicas de Neon y Argón en la roca de Getafe (abundancias en millones de átomos/g)

	^{20}Ne	$^{21}Ne/^{20}Ne$	$^{22}Ne/^{20}Ne$	^{36}Ar	$^{40}Ar/^{36}Ar$	$^{38}Ar/^{36}Ar$
350°C	351	0.00348	0.0963			
±	7	0.00045	0.0014			
700°C	13000	0.00304	0.1025	35700	298.25	0.1937
±	27	0.00004	0.0002	83	0.66	0.0006
1100°C	14400	0.00299	0.1026	163000	299.20	0.1884
±	23	0.00004	0.0001	291	0.50	0.0006
1600°C	1190	0.00337	0.1024	30600	297.83	0.1908
±	9	0.00019	0.0008	74	0.65	0.0005
Total	28900	0.00303	0.1025	233000	298.87	0.1895
±	37	0.00003	0.0002	368	0.40	0.0004

Errors represent 68 % confidence level. Abundances are, isotopic ratios are not blank corrected.

exposure[9], P_{21} = 30,000 atoms/gram/year, we calculate a space exposure age of <97 years. Alternatively, if we consider only a terrestrial history, and adopting the cosmic ray production rate of ^{21}Ne in terrestrial silicon[10], P_{21} = 45 atoms/gram Si/year, corrected for latitude and altitude[11], P_{21} = 74 atoms/gram Si/year, and the silicon abundance (7.6 %), we obtain a terrestrial surface exposure age of < 520,000 years. Using modeled terrestrial surface exposure ^{21}Ne-production rates taking into account contributions from Na, Mg, Al, Si, Ca, Fe[12], we obtain P_{21} = 19 atoms/gram/year, and derive an age of < 149,000 years. All these ages are upper limits because a small ^{22}Ne excess (1,100 °C fraction) suggests either a nucleogenic contribution from the ^{19}F(α,n)^{22}Ne reaction or a trapped Ne signature distinct from atmospheric Ne (Fig. 7).

The argon concentration (^{36}Ar = 8.65·10^{-9} cm^{3}STP/g) and isotope ratios, which barely exceed the atmospheric value, imply a limit of radiogenic ^{40}Ar < 2.34·10^{-8} cm^{3}STP/g, which coupled to the measured potassium abundance (166 ppm) yields a maximum gas retention age of 27.6·10^6 years. Minor variations are also observed in the ^{38}Ar/^{36}Ar ratios and indicate a nucleogenic component or fractionation effects.

The ^{14}C activity ($T_{1/2}$ = 5,730 a) was determined in a bulk powder sample and also in the acid soluble phase and in the residue of the treated sample. The bulk sample has a C concentration of 0.38 % (by weight) and a ^{14}C activity of (1.037 ± 0.009) times modern terrestrial C, or 51.6 (0.5 dpm/kg. The acid-soluble phase revealed a fraction

of (1.079 ± 0.006) and the residue one of (0.870 ± 0.008) times modern terrestrial. If interpreted as an activity induced by cosmic rays in space, this would correspond to a close to saturation activity. However, the activities observed in different phases (acid soluble vs. acid insoluble) are very different and do not agree with typical activities induced in space.

To check the possibility that cosmic-ray produced Ne could have been lost from the rock, ^{10}Be in the bulk rock was also measured; the activity was extremely low with an upper limit of 0.01 dpm/kg. Therefore, both nuclides, stable ^{21}Ne and radioactive ^{10}Be allow upper limits for the space exposure time of 103 years. A possible interpretation could be that the carbon is terrestrial material. Carbon with a "fraction of modern" of 1.03 to 1.08 can only have been formed in the period of 1955-1958 AD and not earlier or more recently.

4. CONCLUSIONS REGARDING ORIGIN

It is puzzling to determine the origin of the GR as it does not match any of the previously classified meteorites, and there are no known rocks (terrestrial or extraterrestrial) which display, as a whole, identical textural, mineralogical and geochemical features. The extreme richness in ultrarefractory elements and mineral phases of the GR approximates the composition to that of coarse-grained CAIs. Dodd[13] includes spinel, melilite, perovskite, anorthite and pyroxene (a similar paragenesis to that of the GR) as major minerals of CAIs. The occurrence of larnite (a high-temperature mineral that is formed at P_{CO_2} of 500 atm and 1,050 °C) in the GR must be emphasized, as it has never been cited in meteorites before. Nevertheless, monticellite, CaMgSiO4 (the series of which encompasses both larnite and forsterite) has been cited in some meteorites (e.g. accesory in Sharps chondrite[14], and in CAIs from the Allende meteorite[15]. The detection of larnite as extraterrestrial mineral phase would open a new line of research for the interpretation of both mineralogical systems and multicomponent interactions during the primeval stage of evolution of the solar system.

The GR also displays an unusual bulk geochemical composition very rich in calcium and iron, and in which the refractory trace elements Zr, Nb, Sr and Ba are extremely high (20 × CI - 800 × CI). In broad terms, it perfectly reflects its mineral

Figure 7. Neon three-isotope plot of Getafe rock with the arrows showing direction of shifts expected from the addition of nucleogenic and cosmic-ray produced spallation components (spallation ratio from Niedermann et al. 1993).

Figura 7. Esquema tri-isotópico de neón de la roca de Getafe con las flechas mostrando las direcciones esperadas a partir de la adición de componentes de spallation nucleogénicos y producidos por los rayos cósmicos (relación de spallation de Niedermann et al. 1993).

paragenesis. Isotopically, oxygen values of the GR are relatively high, fitting the terrestrial fractionation line. But they are also consistent with those found in other meteorites (e.g. Alais, Ivuna and Orgueil chondrites[16]). High values of ^{18}O and ^{17}O can be explained as a significant interaction with a ^{16}O-poor, gas source[17]. Clayton et al.[18] calculated that the initial isotopic ratios of gas which made up the non-fractionated solar system reached values of $\delta^{18}O = +30.0$ ‰ and $\delta^{17}O = +24.2$. Very recently, some authors[19, 20] have stressed that oxygen signatures in CAIs were affected by exchanges with reservoirs of different isotopic composition following crystallization, and that oxygen isotope exchange also occurred during subsequent reheating events in the solar nebula. Space and terrestrial exposure ages calculated for the GR from cosmic ray records (see above and table 1) do not exceed 1,000 and 520,000 years, respectively.

The possibility that the GR is a man-made high technology rock has also been considered. Ceramic and refractory tiles used as thermal protection systems include some calcium silicates and other compounds (e.g. chromite) which are present in the GR. But the different refractory tiles that have been checked (e.g. HRSI, LRSI, FRSI, FRCI, among other materials), display mineralogical and geochemical compositions (rich in C-C, C-SiC and SiC-SiC, silica fibers, Al_2O_3, B_4Si, nylon, etc.), which clearly differ from those found in Getafe[21-24]. A second possibility could be that the GR is the result of some type of high-temperature experiment carried out in Space. The only artificial material which presents some compositional similarities to the GR is a specific type of primary steelmaking slag: namely Electric Arc Furnace (EAF) slags. These EAF slags are crystalline solids, with the textural and chemical appearance of igneous rock, which have a high density (2.4 g/cm3 -approximately half that of GR-) and a compositional variability depending on the proportion in which components are artificially mixed. The mean composition of EAF slags is: CaO: 40.40; MgO: 3.70; SiO_2: 25.20; Al_2O_3: 4.80; FeO: 18.50; MnO: 6.50; TiO_2: 0.30. The mineralogy of the steelmaking slags is characterized by the presence of di-and tricalcic silicates, ferrites, iron and manganese oxides and free CaO. In fact, free CaO (which is absent in the GR) is the main component which typifies the composition and industrial applications of this type of slag. Despite this conspicuous absence, the frequent occurrence

of larnite and wustite in EAF slags should be taken into account if the GR were proven to be a material which, despite possibly coming from the space, could have a terrestrial origin.

In short, it is difficult to conclude, without reasonable doubt, what the real origin of the GR is. Could it be an unusual (and unique) CAI-type extraterrestrial rock, which underwent significant isotopic fractionation, and which, despite this, still preserves remains of the nucleogenic contribution such as those reflected by the small ^{22}Ne excess (1,100 °C fraction), and the minor variations of the $^{38}Ar/^{36}Ar$ ratios? This would support the theory of CAI accumulation in kilometre-sized bodies (*piñatas*) with relatively stable orbits, during the first differentiation stages of the primitive solar nebula[25]. In fact, this author points out, citing W.R. Skinner, that the large CAI-filled *piñatas* would have to be broken apart 10 Ma later, releasing the CAIs for incorporation into chondritic bodies. Or could it simply be the result of a high-tech artificial experiment developed in Space? Previous works have indicated that a surprising relationship between the characteristics of CAIs and industrial slags exists. This relationship was evidenced, for the first time, when the Allende CAI inclusion rims and refractory bricks from a British steel furnace were compared[26]. These authors stated that whereas artificial refractory bricks are simpler in composition than CAI inclusions, the thermal alteration textures are very similar to CAI rims (e.g. Allende CAI inclusion rims). Since then, other authors[27-29] have stressed the importance of the study of some industrial products in order to understand the genesis and transformations of extraterrestrial matter.

Museums and universities are frequently presented with samples suspected by the owners of being meteorites. In the overwhelming majority of cases, the 'meteorites' are assorted forms of sedimentary, igneous or metamorphic rocks, or industrial slags, often with unusual shapes or textures which triggered the imagination of the discoverer. Vesiculated blast-furnace slags apart, some metallurgical products are amongst the harder cases to identify. The Getafe study addresses one such case, in spite the fact that the circumstances surrounding the fall are very well documented and verified. At present, all the investigation carried out to date concerning the GR addresses this dilemma: terrestrial vs. extraterrestrial, and no definite conclusion can be

reached. The controversial genesis of this enigmatic rock should now be open to scientific debate.

Acknowledgements

References

[1] J. MARTÍNEZ-FRIAS, *Dept. Com. y Prensa, CSIC* (1994) pp. 1-3.

[2] J. MARTÍNEZ-FRÍAS *Dirección General de Investigación Científica y Técnica, DGICYT*, APC96, 1998, pp. 1-4.

[3] G. KURAT, C.H. KOEBERL, T. PRESPER, F. BRANDSTÄTTER and M. MAURETTE, *Geochim. Cosmochim. Acta* 58 (1994) 3879-3904.

[4] D. WEBER, E. ZINNER and A. BISCHOFF, *Geochim. Cosmochim. Acta* 59 (1995) 803.

[5] S. YONEDA and L. GROSSMAN, *Geochim. Cosmochim. Acta*, 59 (1995) 3413-3444.

[6] B.E. NESBITT and W.C. KELLY, *Proc. Ann. Conf. Microbeam Anal. Soc.* 13, 95, 1978, pp. 123-128.

[7] K. MARTI and T. GRAF, *Annu. Rev. Earth Planet. Sci.* 20 (1992) 221-243.

[8] S. NIEDERMANN, T.H. GRAF and K. MARTI, *Earth Planet. Sci. Lett.* 118 (1993) 65-73.

[9] O. EUGSTER *Geochim. Cosmochim. Acta* 52 (1988) 1649-1662.

[10] S. NIEDERMANN, TH. GRAF, J.S. KIM, C.P. KOHL, K. MARTI and K. NISHIIZUMI, *Earth Planet. Sci. Lett.* 125 (1994) 341-355.

[11] D. LAL, *Earth Planet. Sci. Lett.* 104 (1991) 424-439.

[12] J. MASARIK and R.C. REEDY, *Radiocarbon* 38 (1996) 163-164.

[13] R.T. DODD, *Meteorites. A petrologic-chemical synthesis*, Cambridge University Press, Cambridge, Inglaterra, 1981, p. 368.

[14] E.A. KING, *Space Geology.* John Wiley & Sons, Inc., EE.UU., 1976, p. 349.

[15] D.A. WARK, W.V. BOYNTON, R.R. KEAYS and H. PALME *Geochim. Cosmochim. Acta* 51 (1987) 607-622.

[16] M. ROWE, R.N. CLAYTON and T.K. MAYEDA, *Geochim. Cosmochim. Acta*, 58 (1994) 5341-5347.

[17] R.N. CLAYTON, *Annu. Rev. Earth Planet. Sci.* 21 (1993) 115-149.

[18] R.N. CLAYTON and T.K. MAYEDA, *Earth Planet. Sci. Lett.* 67 (1984) 151-161.

[19] K.D. MCKEEGAN, L.A. LESHIN, S.S. RUSSELL and G.J. MACPHERSON *Science*, 280 (1998) 414-418.

[20] H. YURIMOTO M. ITO and H. NAGASAWA, *Science* 282 (1998) 1874-1877.

[21] P.R. BECKER, *Am. Cer. Soc. Bull.* 60 (1981) 1210-1214.

[22] J. Mª RINCÓN, *Quím. Ind. Madrid* 31 (1985) 95-99.

[23] W.P. KEITH, *Am. Cer. Soc. Bull.* 68 (1989) 1307-1308.

[24] M. AUWETERKURTZ, H. HALD, G. KOPPENWALLNER and H.D. SPECKMANN, *Acta Astronautica* 38 (1996) 47-61.

[25] A.P BOSS, *Nature* 375 (1995) 13-14.

[26] T.E. BUNCH and S. CHANG *Meteoritics* 15 (1980) 270-271.

[27] J.M. PAQUE, J.R. BECKETT, D.J. BARBER and E.M. STOLPER, *Meteoritics* 29 (1994) 673-682.

[28] D.J. BARBER and S.O. AGRELL, *Meteoritics* 29 (1994) 691-695.

[29] D.J. BARBER, J.R. BECKETT, J.M. PAQUE and E. STOLPER *Meteoritics* 29 (1994) 682-690.