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'San Juan', a new mass of the Campo del Cielo meteorite shower

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ABSTRACT

Petrographic and chemical (major, minor and trace element) studies of silicate inclusions and metal from the San Juan A and B samples revealed that they are new masses belonging to the Campo del Cielo IAB iron meteorite shower. These masses must have being transported from the large strewn field in the Chaco and Santiago del Estero Provinces to the surroundings of San Juan city, where they have being recover in the year 2000. The sizes of the two masses of San Juan, collected 770 km SW from Santiago del Estero, is in agreement with the previously suggested anthropic hypothesis for the transport of Campo del Cielo.

Keywords: IAB iron meteorites, Campo del Cielo meteorite, San Juan meteorite.

RESUMEN

San Juan, una nueva masa de la lluvia de meteoritos de Campo del Cielo.
Estudios petrográficos y químicos (elementos mayores, menores y trazas) de inclusiones de silicatos y de metal de las muestras A y B de San Juan, reveló que son nuevas masas que pertenecen a la lluvia de meteoritos de Campo del Cielo. Estas masas deben haber sido transportadas desde el gran campo de dispersión en las provincias de Chaco y Santiago del Estero a los alrededores de la ciudad de San Juan, donde se han recuperado en el año 2000. Los tamaños de las dos masas de San Juan, cotejados a 770 km al SO de Santiago del Estero, están de acuerdo con las hipótesis antrópicas previamente sugeridas para el transporte de Campo del Cielo.

Palabras clave: Meteoritos de hierro IAB, meteorito Campo del Cielo, meteorito San Juan.

INTRODUCTION

The IAB iron meteorites are a large group of irons, sometimes refer to as "IAB complex iron meteorites", that differ chemically and texturally from the so-called "magmatic iron groups" (e.g., IIAB, IIIAB, and IVA, Scott 1972, Scott and Wasson 1975). The IAB iron meteorites have chemical composition (major and trace element ratios) that do not fit a fractional crystallization model (e.g. Scott 1972, Wasson and Kallemeyn 2002, Goldstein et al. 2009). In addition, some IAB iron meteorites have silicate inclusions, which are scarce or absent in iron meteorites from the magmatic groups. Therefore, the IAB iron meteorites are referred to as ''non-magmatic" or ''silicate-bearing" (e.g., Wasson 1970). Some silicate inclusions show chondritic chemical composition and isotopic similarity to a group of primitive achondrites named winonaites (Benedix et al. 2000). This similarity could indicate that some IAB meteorites may share the same parent body as the winonaites (Bild 1977, Clayton and Mayeda 1996). However, and due to the unusual chemical and textural characteristics of the IAB iron meteorites, currently there is no consensus on the formation scenario of this group.

Campo del Cielo, the largest iron meteorite in the world from the viewpoint of recovered mass (total weight of the pieces so far recovered is about 100 tonnes), is a member of the main group (MG) of the non-magmatic iron meteorite group IAB (Wasson and Kallemeyn 2002). It fell as a vast shower covering a large strewn field in the Chaco and Santiago del Estero Provinces of northern Argentina (Cassidy et al. 1965).

In the year 2000 a small (760 g) and a large (50.25 kg) piece of meteoritic iron were found in a limestone quarry near the San Juan city of Argentina (~770 km SW from Santiago del Estero) and were named as San Juan A and B, respectively (Figs. 1, 2). From San Juan B nine slices, comprising a total of 8,840 g, were cut for different purposes (e.g., museum exhibitions, research, etc. Figs. 3, 4). The main mass of San Juan B is deposited at the La Plata Museum (Argentina). In this paper, we provide a petrographic and chemical (major and trace elements) study of the San Juan A-B silicate inclusions, compared them with silicate inclusions in other IAB irons and indicate that San Juan mass could be considered as a piece of the Campo del Cielo meteorite shower. The formal approval of San Juan as additional masses of Campo del Cielo by the Nomenclature Committee of the Meteoritical Society is pending.

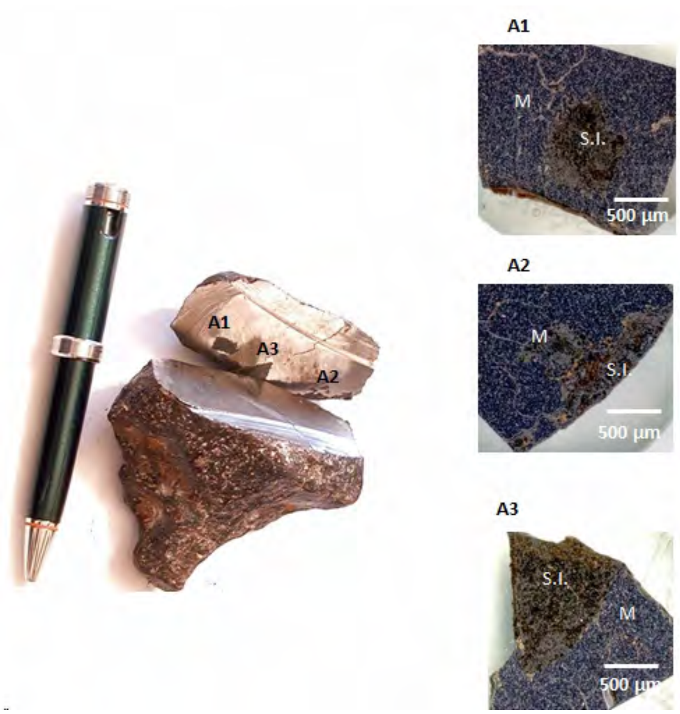

Figure 1. The San Juan A mass and a view of the slide where the three silicate inclusions (A1, A2 and A3) are seen. A detail of the three polished sections A1, A2 and A3 are shown. M: Metal; SI: Silicate Inclusion.

Figure 2. The San Juan B piece, with a total mass of 50.25 kg. Total length: 40 cm.

SAMPLES AND ANALYTICAL TECHNIQUES

Samples were studied by optical microscopy for the petrographic characteristics of the constituent phases (e.g. silicate inclusions, metal). Major element chemical compositions of constituent phases were obtained with a JEOL 6400 and a JEOL JSM-6610 scanning electron microprobe (NHM, Vienna) operated at a sample current of 1 nA and an acceleration voltage of 15 kV and with an ARL-SEMQ (ICATE), a SX100 (Institute of Geological Sciences, University of Vienna) and a JEOL JXA-8530F FE (NHM, Vienna) electron microprobes. The standards apply are as follow: synthetic Al2O3 (Al); natural olivine (Fe, Mg); natural orthopyroxene (Si); natural wollastonite and augite Chrom 164905 (Ca); synthetic rutile and horblende Kakanui 143965 (Ti); Cr2O3 (Cr), tephroite (Mn); KCl and microcline 143966 (K); and Anorthoclase 133868 and NaCl (Na). Electron microprobe analyses (EMPA) were performed using a 15 kV acceleration potential and a beam current of 20 nA and a counting time of 10 s for peak and 5 s for background. Trace element analyses of silicate phases were made with the Cameca IMS 3f ion microprobe at Washington University, St. Louis, following a modified procedure of Zinner and Crozaz (1986). The LA -ICP-MS of metal were performed following the procedures of Campbell et al. (2001).

The polished-thick section of San Juan A1, A2, A3 and B belongs to the collection of the NHM (Vienna) (inventory number: NHMV-02001; NHMV-O333; NHMV-026 and NHMV-02002, respectively).

RESULTS

Petrography and major element composition

The small San Juan A mass is a coarse octahedrite, which has three angular silicate inclusions of up to 1 cm^2 in size (Fig. 1). Polished sections were performed from each inclusion and named after: San Juan A1, A2 and A3 (Fig.1). The San Juan A and B samples show similar petrographic characteristics. They are graphite peridotites consisting of olivine, graphite, orthopyroxene, plagioclase, clinopyroxene and small amounts of metal and sulfide.

The texture of all four samples is coarse-granular with grain sizes varying from place to place. They consist of magnesian olivine ($Fo_{94.9-94.6}$) and orthopyroxene ($En_{90.6}$, $Fs_{7.7}$, $Wo_{1.7}$ to $En_{92.7}$, $Fs_{6.12}$, $Wo_{1.22}$), albitic plagioclase ($An_{14.65-13.5}$), High-Ca pyroxene ($En_{52.9}$, $Fs_{3.4}$, $Wo_{43.7}$ to $En_{52.1}$, $Fs_{1.28}$, $Wo_{46.6}$), and graphite (Table 1). The later composition is omnipresent inside the silicate inclusion, filling intergranular and interaggregate space and covering the inclusion surface (Fig. 3). Cliftonite and multiple intergrowths are abundantly present in kamacite of the octahedrite metal.

Trace element composition

Trace element contents of olivine, plagioclase, orthopyroxene and clinopyroxene (Table 2) are akin to analogous mineral phases in other IAB meteorites (e.g., Udei Station, Fig. 4 a-b). The metal matrix is homogeneous and contains 6.3 wt% Ni and 0.46 wt% Co (Kurat et al. 2002). Besides the octahedrite (metal matrix); metal is present as: Metal Islands (MI) occurring as embayment in silicate inclusions; as small inclusions in graphite (MG: Metal in graphite) and forming veins (MV: Metal Vein). Despite their different occurrences, they are fairly similar with respect to its Ni and Co contents that varies between 5.6-6.3 wt% Ni and 0.46-0.51 wt% Co. Moreover, the abundances of the siderophile elements in metal having different occurrences (e.g., MI, MG, MI) are similar (Fig. 5). Only a slight fractionation is observed whether the metal is present in the octahedrite, as metal vein, as embayment shapes in silicate inclusions forming metal islands, or if it is finely dispersed in the graphite.

DISCUSSION

Abundances of silicate inclusions in silicate-bearing IAB irons can range widely from Smithville in which silicates are rare phases (Buchwald 1975), to Campo del Cielo in which

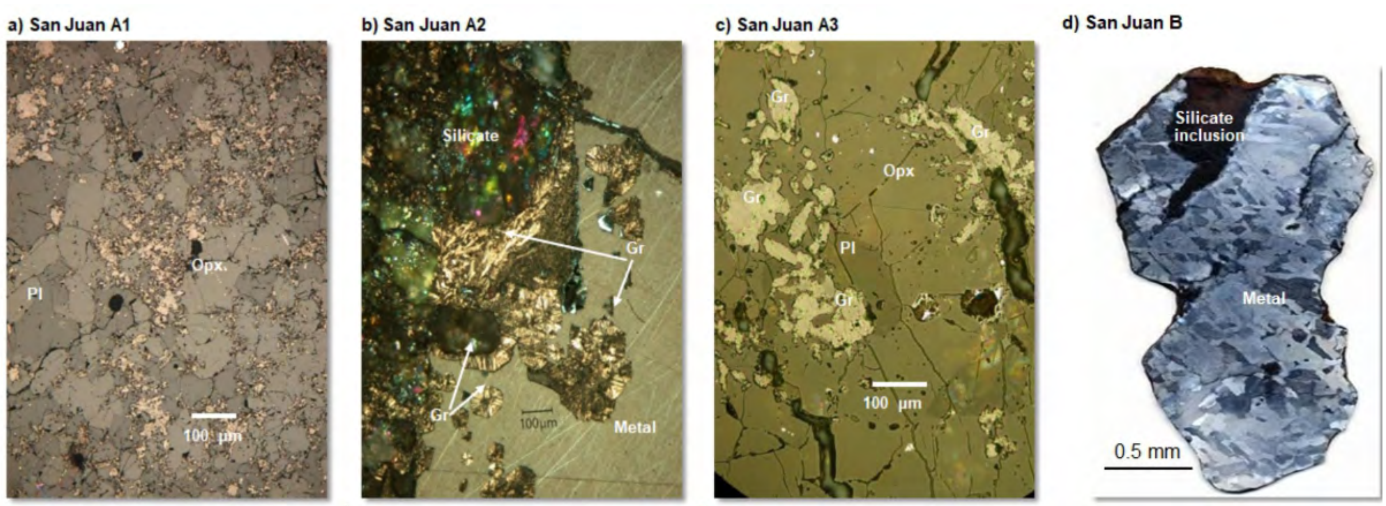

Figure 3. a) Photomicrograph of San Juan A1 in reflective light showing the coarse-granular texture of the silicate inclusions. Graphite (Gr) seems to be preferably related to plagioclase; b) Photomicrograph of San Juan A2 in crossed polarized light showing the abundance of graphite forming feathery patches inside the silicate inclusion, radial rims between the silicate inclusion and metal and as cliftonite inside metal; c) Photomicrograph of San Juan A3 in reflective light showing the graphite can be interchangeable associated to plagioclase (Pl.) and orthopyroxene (Opx); d) Polished slice of San Juan B (829.8 g) exhibited at the La Plata museum (Argentina). Total length: 20 cm.

Table 1. Chemical composition of mineral phases from San Juan A1 (mean value of four areas, in wt%)

	Plagio-clase	SD	Low-Ca Pyx	SD	High-Ca Pyx	SD	Olivine	SD
N	11		36		12		9	
SiO_2	63.5	0.51	58	0.73	54.5	0.64	42.4	0.36
TiO_2	0.04	0.01	0.2	0.02	0.66	0.02		
Al_2O_3	22.3	0.44	0.28	0.04	0.79	0.04		
Cr_2O_3			0.34	0.06	1.3	0.07		
FeO	0.3	0.18	4.56	0.36	1.51	0.24	4.8	0.47
MnO			0.53	0.02	0.29	0.02	0.43	0.03
MgO			35.7	0.63	18	0.15	53.7	0.33
CaO	3.11	0.2	0.82	0.15	22.4	0.32		
Na_2O	10.2	0.64			0.84	0.06		
K_2O	0.74	0.36						
Total	100.2		100.4		100.3		101.3	
Mole percent mineral end members								
An	13.9							
Ab	82.2							
Or	3.9							
Wo			1.5		46.6			
En			92.2		52.1			
Fs			6.2		1.3			
Te							0.4	
Fo							94.8	
Fa							4.8	

Chemical composition of mineral phases from San Juan A2 (mean value of the seven areas. in wt%)

	Plagio-clase	SD	Low-Ca Pyx	SD	High-Ca Pyx	SD	Olivine	SD
N	18		64		9		30	
SiO_2	63.5	0.37	57.4	0.23	53.1	1.12	40.4	0.2
TiO_2	0.08	0.01	0.25	0.01	0.71	0.04	0.03	0.01
Al_2O_3	21.9	0.1	0.26	0.01	1.1	0.35		
Cr_2O_3	0.02	0.01	0.36	0.03	1.09	0.2	0.02	0.01
FeO	0.33	0.09	4.56	0.07	2.17	0.5	4.77	0.2
MnO	0.02	0.01	0.51	0.01	0.24	0.02	0.4	0.03
MgO	0.01		37	0.17	19.2	0.37	54.4	0.4
CaO	3.13	0.05	0.77	0.05	22.1	0.02		
Na_2O	10.1	0.14	0.04	0.002	0.67	0.2		
Total	99.09		101.15		100.38		100.02	
Mole percent mineral end members								
An	14.65							
Ab	85.35							
Wo			1.68		43.71			
En			90.57		52.94			
Fs			7.75		3.36			
Te							0.38	
Fo							94.9	
Fa							4.67	

Chemical composition of mineral phases from San Juan A3 (wt%)

	Plagioclase	SD	Low-Ca Pyx	SD	Olivine	SD
N	439		595		154	
SiO_2	64.9	0.63	58.52	0.4	42.6	0.73
TiO_2	0.07	0.03	0.21	0.03	0.02	0.02
Al_2O_3	21.9	0.39	0.24	0.03		
Cr_2O_3	0.02	0.02	0.34	0.07	0.07	0.05
FeO	0.36	0.51	4.1	0.31	4.64	0.28
MnO	0.02	0.02	0.52	0.04	0.4	0.06
MgO	0.01	0.01	34.83	0.61	52.3	0.74
CaO	3.21	0.12	0.64	0.12		
Na_2O	8.6	0.58	0.02	0.02		
Total	99.09		99.42		100.03	
Mole percent mineral end members						
An	16.52					
Ab	79.8					
Or	3.68					
Wo			1.22			
En			92.67			
Fs			6.12			
Te					1.03	
Fo					94.8	
Fa					4.17	

Chemical composition of mineral phases from San Juan B (wt%)

	Plagioclase	Low-Ca Pyx	SD	High-Ca Pyx	SD	Olivine	SD
N	1	3		6		3	
SiO_2	65.1	59.1	0.43	55.5	0.4	41.6	0.8
TiO_2		0.21	0.04	0.69	0.05		
Al_2O_3	21.8	0.25	0.02	0.75	0.04		
Cr_2O_3		0.34	0.01	1.12	0.18		
FeO	0.2	4.43	0.53	1.99	0.28	5.00	1
MnO		0.52	0.04	0.27	0.03	0.42	0.07
MgO		36.1	0.7	18.2	0.26	53.7	0.7
CaO	3.1	0.68	0.2	21.4	0.35		
Na_2O	10.1			0.78	0.1		
K_2O	0.5						
Total	100.08	101.63		100.7		100.72	
Mole percent mineral end members							
An	14.1						
Ab	83.2						
Or	2.71						
Wo		1.25		44.3			
En		92.4		52.5			
Fs		6.4		3.22			
Te						0.42	
Fo						94.6	
Fa						4.94	

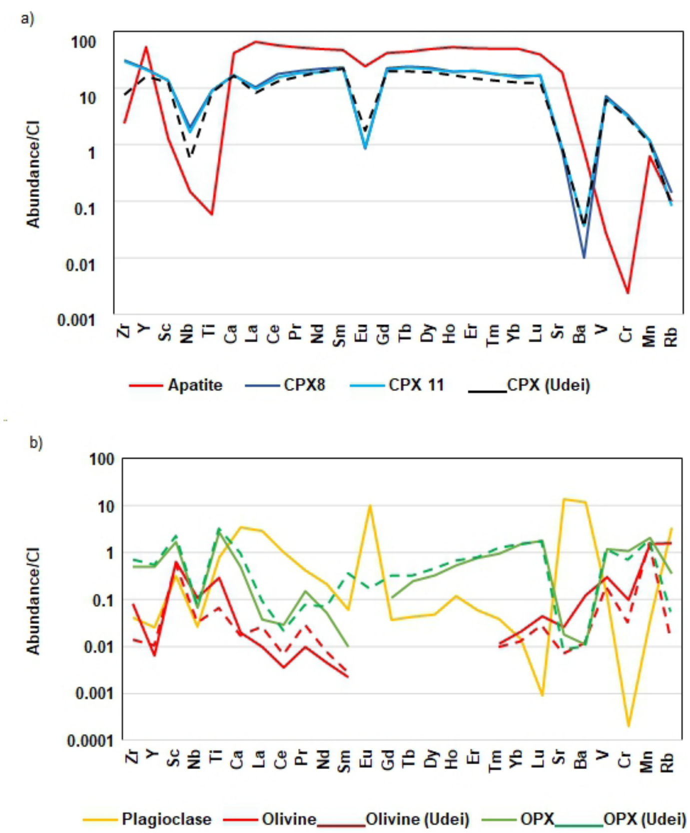

Figure 4. CI-normalized trace element abundances in silicate phases of San Juan A1 (normalizing data from Lodders and Fegley 1998). Elements are ordered according to decreasing 50% condensation temperature (Lodders 2003), except for the REEs, which are ordered by increasing atomic number. Cpx= clinopyroxene; OPX= low-Ca pyroxene; Udei: Udei Station (Ruzicka and Hutson, 2010)

they are more abundant (e.g., Tomkins et al. 2013). These silicate inclusions can be grouped depending on the richness of different phases as follow: Sulfide-rich, Silicate-rich, Graphite-rich and Phosphate-bearing (Benedix et al. 2000). The silicate-rich inclusions are subdivided in: non-chondritic and angular chondritic type. The shape and texture of the San Juan silicate inclusions allow to classify them as angular chondritic silicate-rich (Benedix et al., 2000). These inclusions are found in several IAB iron meteorites as: Campo del Cielo (Wlotzka and Jarosewich 1977, Bild 1977); Copiapo (Bunch et al. 1970), Caddo County (Takeda et al. 1993, 2000), Ocotillo (Olsen and Schwade 1998) and Zagora (Dominik and Bussy 1994), among others (see Table 3, Benedix et al. 2000).

The chemical composition of the silicate phases in San Juan are similar to those found in other IAB iron meteorites (Table 3) being Fe- poor ($Fa_{4.17\text{-}4.94}$- $Fs_{7.7}$, $Wo_{1.7}$ - $Fs_{6.12}$, $Wo_{1.22}$) and, therefore akin to those found in Campo del Cielo (Fa_4-$Fs_{6.6}$, $Wo_{1.2}$). These angular chondritic silicate-rich inclusions have the most Fe-poor silicate mineral composition in any inclusions in the IAB iron meteorites (Benedix et al. 2000). Chromite from silicate-bearing iron meteorites, as well as those present in San Juan samples, are in contrast with a typical chondritic composition as they are rich in MgO with substantial amounts of Al and Zn (Table 4).

The homogeneous concentration of Ni (6.3 wt%) and Co (0.46 wt%) in the metal matrix (Kurat et al. 2002) is placed within the range of the iron meteorites with Campo-like compositions that vary between 6.30 - 7.14 wt% Ni and 0.47 – 0.478 wt% Co (Wasson 2018).

A strong indication towards San Juan being a mass of Campo del Cielo is that the trace element abundances of all types of metal (e.g., M, MI, Mg, etc., Fig. 5) follow exactly the pattern of bulk Campo del Cielo (Jochum et al. 1980, Choi et al. 1995, Hoashi et al. 1993).

Graphite in San Juan sample occurs as inclusions in silicates, it fills intergranular space between silicates, and covers the inclusion's surface. Graphite intergrowths are also present in kamacite of the octahedrite metal. All these graphites show different $\delta^{13}C$ (relative to PDB) values (Maruoka et al. 2003). The graphite in the silicate inclusion has constant $\delta^{13}C$ values (-3.7 ± 4.3), akin to that of graphite in silicate inclusions in several IAB iron meteorites (Deines and Wickman 1973, 1975, Sugiura 1998). However, graphite masses covering the surface of the inclusion show lower $\delta^{13}C$ values (-13.2 ± 5.6) and are different to those others embedded in the metal (-17.3 ± 6.7). Similar carbon isotopic heterogeneity of graphite nodules was found in the El Taco mass of Campo del Cielo and should be the result of mixing between carbon originating from the inclusion and carbon exsolved from taenite (Zipfel et al. 1997). This mixing process denotes high temperatures to dissolve graphite into metal. If so, graphite isotopic composition should have been homogenized. Marouka's results leave an open question regarding the thermal process (if any) linked to the presence of graphite in San Juan masses of Campo del

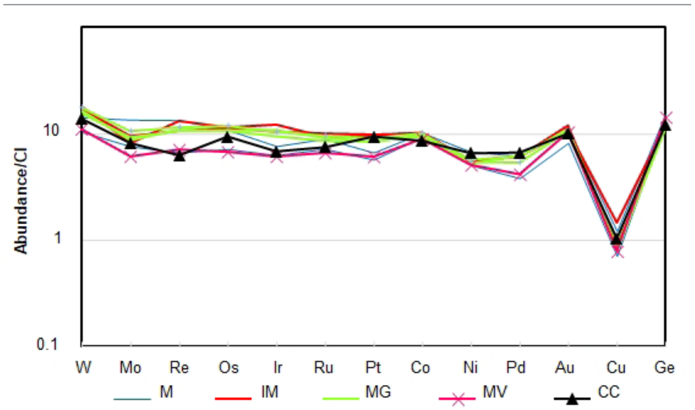

Figure 5. CI-normalized (Lodders and Fegely, 1998) trace element abundances in metal from San Juan A2 compared to Campo del Cielo bulk composition. M: octahedrite; IM: Metal Islands occurring as embayment in silicate inclusions; MG: metal in graphite; MV: metal vein; CC: Campo del Cielo.

Table 2. Secondary ion mass spectrometry (SIMS) analyses of silicate phases in San Juan

Element	Apatite	Error	CPX8	Error	CPX11	Error	Plagioclase	Error	Olivine	Error	Orthopyroxene	Error
Zr	9.06	0.260	119	0.809	114	0.799	0.16	0.008	0.31	0.014	1.83	0.042
Y	80.7	0.484	33	0.281	32	0.280	0.04	0.002	0.009	0.001	0.76	0.019
Sc	7.33	0.084	77	0.556	78	0.561	1.77	0.056	3.6	0.042	9.1	0.067
Nb	0.04	0.005	0.49	0.035	0.4	0.030	0.006	0.001	0.03	0.002	0.02	0.002
Ti	24.6	0.862	3862	4,652	3777	4,640	328	0.329	122	0.193	1093	0.636
Ca	372750	130	151700	546	155200	548	30450	28	174	0.18	4281	1
La	15	0.259	2.37	0.095	2.22	0.093	0.64	0.022	0.0022	0.001	0.009	0.001
Ce	33.5	0.433	10.4	0.227	9.06	0.214	0.59	0.024	0.0021	0.001	0.017	0.002
Pr	4.5	0.135	1.74	0.082	1.61	0.073	0.04	0.003	0.0008	0.0002	0.013	0.0009
Nd	21.6	0.394	9.7	0.224	8.42	0.220	0.09	0.005	0.0019	0.0004	0.023	0.0013
Sm	6.7	0.334	3.3	0.154	3.22	0.171	0.009	0.001				
Eu	1.32	0.061	0.047	0.010	0.05	0.012	0.53	0.021				
Gd	7.96	0.393	4.3	0.258	4.05	0.252	0.007	0.002	0.02	0.003		
Tb	1.56	0.102	0.84	0.057	0.82	0.048	0.0015	0.0004	0.009	0.001		
Dy	11.5	0.294	5.4	0.168	5.08	0.162	0.01	0.001	0.07	0.004		
Ho	2.85	0.122	1.06	0.064	1.1	0.059	0.006	0.001	0.03	0.002		
Er	7.8	0.230	3.08	0.106	3.2	0.122	0.009	0.001	0.11	0.006		
Tm	1.17	0.062	0.41	0.028	0.42	0.030	0.0009	0.002	0.0003	0.0001	0.02	0.002
Yb	7.8	0.257	2.6	0.131	2.42	0.152	0.002	0.001	0.0032	0.0006	0.23	0.010
Lu	0.93	0.078	0.39	0.036	0.4	0.037	0.0002	0.001	0.0003	0.04	0.003	
Sr	144	2,032	6.02	0.163	6.7	0.161	102	0.255	0.19	0.008	0.14	0.007
Ba	1.77	0.092	0.02	0.008	0.08	0.010	26	0.172	0.28	0.010	0.025	0.003
V	1.49	0.061	400	0.938	366	0.903	6.5	0.050	16	0.080	62	0.172
Cr	6.2	0.383	8687	6,428	8150	6,182	0.6	0.019	250	0.355	2680	1,535
Mn	1200	2,304	2317	2,877	2275	2,872	68	0.203	2917	1,468	3780	1,885
Rb	0.22	0.019	0.32	0.260	0.19	0.270	7.5	0.321	3.5	0.070	0.77	0.054

Cielo (IAB) iron meteorite.

Preliminary results on Xe isotopic composition in San Juan A2 silicates and graphite inclusions are consistent with a mixture of two major components – air (introduced by cutting and polishing) and iodine-derived Xe (Pravdivtseva et al. 2017). Accordingly, the $^{22}Ne/^{21}Ne$ values in San Juan A2 silicates and graphite have an average value of 1.04, consistent with irradiation in a large body at a large shielding depth. Based on the pre-atmospheric size of Campo del Cielo (with a radius larger than 3 m, Liberman et al. 2002), the San Juan samples were well shielded from primary cosmic ray high-energy irradiation (Pravdivtseva et al. 2017).

According to Wasson 2018 *"The Campo terrestrial age of 4 ka* (Liberman et al. 2002) *is relatively recent, about 10 ka after Homo sapiens arrived in this part of South America. One, therefore, expects that Campo samples have been transported across large areas of southern South America and been rediscovered in recent times."* Consequently, masses of Campo del Cielo might have been transported all across the southern half of South America (Wasson 2018). Many could have been recovered as single masses depending on the transport distances. The transported meteorites will have a limited size range (e.g., 2–50 kg, Wasson 2018). This, seems to have been the case of these 'San Juan' masses of Campo del Cielo.

CONCLUSION

The shape of the graphite peridotite silicate-rich inclusions, their textures, the chemical composition of silicates and metal, as well as the trace element abundances of metal indicate that the San Juan masses can be considered as two new masses of Campo del Cielo (IAB) meteorite shower and represent transported samples of Campo. We shall therefore refer to these samples as the San Juan mass of Campo del Cielo in order to distinguish them from others like the El Taco mass (Wlotzka and Jarosewich 1977, Bild1977).

Table 3. Average composition of silicates in San Juan and other IAB iron meteorites

	Plagioclase			Low-Ca Pyx		
	Mean San Juan	Bild 1977	Benedix et al. 2000	Mean San Juan	Bild 1977	Benedix et al. 2000
SiO_2	64.25	63.8	64.4	58.26	58.6	57.9
TiO_2	0.06			0.22	0.22	0.2
Al_2O_3	21.98	23	22.6	0.26	0.32	0.24
Cr_2O_3	0.02			0.35	0.21	0.31
FeO	0.30			4.41	3.76	4.47
MnO	0.02			0.52	0.32	0.35
MgO	0.01			35.91	36	36.24
CaO	3.14	4.03	3.19	0.73	0.81	
Na_2O	9.75	9.14	9.42	0.03		
K_2O	0.62	0.68	0.62			
Total	100.15	100.65	100.23	100.67	100.24	99.71
	High-Ca Pyx			**Olivine**		
	Mean San Juan	Bild 1977	Benedix et al. 2000	Mean San Juan	Bild 1977	Benedix et al. 2000
SiO_2	54.37	54.7	54.8	41.75	42.06	41.8
TiO_2	0.69	0.6	0.67	0.03		
Al_2O_3	0.88	0.77	0.87			
Cr_2O_3	1.17	1.1	1.13	0.05		
FeO	1.89	2	1.82	4.80	3.58	3.81
MnO	0.27	0.25	0.24	0.41	0.21	0.32
MgO	18.47	18	18.1	53.53	53.8	54
CaO	21.97	21.6	21.82			
Na_2O	0.76	0.67	0.76			
K_2O						
Total	100.46	99.69	100.21	100.57	99.65	99.93

Table 4. Chemical composition of chromite from San Juan (wt%)

	San Juan	Bild 1977
FeO	13.04	12.3
MgO	10.91	10.2
MnO	2.23	2.5
ZnO	1.99	1.75
Cr_2O_3	70.77	71.3
Al_2O_3	0.93	0.27
TiO_2	0.59	0.43
Total	100.46	98.75

Bild 1977: Analysis of Winona chromite

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