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Santa Lucia (2008) (L6) Chondrite, a Recent Fall: Composition, Noble Gases, Nitrogen and Cosmic Ray Exposure Age

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Abstract The Santa Lucia (2008)—one the most recent Argentine meteorite fall, fell in San Juan province, Argentina, on 23 January 2008. Several masses (total ~6 kg) were recovered. Most are totally covered by fusion crust. The exposed interior is of light-grey colour. Chemical data [olivine ($Fa_{24.4}$) and low-Ca pyroxene ($En_{77.8}\,Fs_{20.7}\,Wo_{1.6}$)] indicate that Santa Luica (2008) is a member of the low iron L chondrite group, corresponding to the equilibrated petrologic type 6. The meteorite name was approved by the Nomenclature Committee (NomCom) of the Meteoritical Society (Meteoritic Bulletin, no. 97). We report about the chemical composition of the major mineral phases, its bulk trace element abundance, its noble gas and nitrogen data. The cosmic ray exposure age based on cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar around 20 Ma is comparable to one peak of L chondrites. The radiogenic K–Ar age of 2.96 Ga, while the young U, Th–He are of 1.2 Ga indicates that Santa Lucia (2008) lost radiogenic ^{4}He more recently. Low cosmogenic (^{22}Ne/^{21}Ne)$_c$ and absence of solar wind noble gases are consistent with irradiation in a large body. Heavy noble gases (Ar/Kr/Xe) indicated trapped gases similar to ordinary chondrites. Krypton and neon indicates irradiation in large body, implying large pre-atmospheric meteoroid.

Keywords Ordinary chondrite · Noble gases · Cosmic ray exposure age

1 Introduction

The Santa Lucia (2008) L6 chondrite fell in San Juan province, Argentina, on 23 Jan. 2008 at 17.20 h. Around 6 kg was recovered. The fresh surface shows a grey homogenous colour with grains of fresh metal and sulphides. The stone investigated is part of one piece of fusion-crusted black stone weighting 1900 g.

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2 Materials and Methods

Five thin polished sections were studied using optical microscope, scanning-electron microscopy (SEM) and electron microprobe. Major element chemical compositions were obtained with a JEOL 6400 analytical scanning electron microscope (ASEM) (NHM; Vienna) and a ARL-SEMQ (WDS) (ICATE, Argentina) electron microprobe. Electron microprobe analyses (EMPA) were performed using a 15 kV acceleration potential and 15 nA sample current. Estimated precision for major and minor elements is better than 3 %, for Na about 10 %. Natural and synthetic standards were used for calibration and a ZAF correction was applied to the data.

Bulk trace element analyses were performed using Instrumental Neutron Activation Analysis (INAA) following the procedure described by Joron et al. (1997). The irradiation was done under Cd-cover and performed using the CEA/Saclay Osiris reactor. After 1 week cooling the first counting for 3000 s allow determination of ^{140}La, ^{153}Sm, ^{24}Na, ^{76}As, and ^{198}Au. After 1 month cooling, samples are counted again for 20 and 40 s for: ^{46}Sc, ^{54}Mn, ^{58}Co, ^{60}Co, ^{65}Zn, ^{85}Sr, ^{86}Rb, ^{95}Zr, ^{110}Ag, ^{131}Ba, ^{134}Cs, ^{141}Ce, ^{147}Nd, ^{152}Eu, ^{160}Tb, ^{169}Yb, ^{181}Hf, ^{182}Ta and ^{192}Ir.

The noble gas and nitrogen analyses were performed on PRL-Noblesse multi collector mass spectrometer. Noble gases and nitrogen were measured in 78.52 mg specimen using step wise heating method. The sample was wrapped in aluminium foil is preheated for about 48 h at 150 °C to desorb loosely bound atmospheric noble gases. Gases were extracted in three heating steps, 600 (45 min), 1200 (45 min) and 1700 °C (25 min) in resistance furnace. Extracted gas was divided into two fractions, one for nitrogen analysis and other for noble gas analysis. Nitrogen fraction was cleaned by oxygen at 2 torr pressure and collecting the volatiles in cold finger with liquid nitrogen trap. Noble gas fraction was cleaned by exposing the gas to getter at 750 °C. Heavy noble gases (Ar–Kr–Xe) were collected on charcoal by liquid nitrogen and the He–Ne in gas was measured. Liquid nitrogen trap was maintained during He–Ne measurements to remove background gases and interfering species. Blanks were run under the same conditions as that of sample run. Typical blanks at 1700 °C (in cm^3 STP for noble gases and ng for nitrogen) are $^{4}He = 26 \times 10^{-10}$, $^{22}Ne = 1.9 \times 10^{-12}$, $^{36}Ar = 2.4 \times 10^{-11}$, $^{84}Kr = 5.1 \times 10^{-14}$, $^{132}Xe = 1.1 \times 10^{-14}$, $N_2 = 5.3$. The measured noble gas concentrations, as listed in Table 1, are accurate to $\sim$10 %. Data reported are corrected for blanks, interferences and mass discrimination. Errors reported include uncertainties derived from the all the correction including volume calibration. For cosmogenic corrections $(^{38}Ar/^{36}Ar)_{tr} = 0.188$ and $(^{38}Ar/^{36}Ar)_c = 1.5$, $(^{20}Ne/^{22}Ne)_c = 0.8$ and $(^{21}Ne/^{22}Ne)_c = 0.9$ (Wieler 2002) are used. ^{40}Ar is assumed to be entirely radiogenic.

3 Results and Discussion

3.1 Petrology and Chemical Composition

In hand specimen almost all pieces are fusion crusted. Broken surfaces expose a light grayish interior with dispersed opaque minerals and scarce delineated oval and spherical chondrules.

Under optical inspection Santa Lucia (2008) shows a chondritic texture similar to other ordinary chondrites with poorly defined chondrules often intergrown with the matrix. It is a

Table 1 Representative EMP analysis of olivine in Santa Lucia (2008)

SiO_2	37.7	38.3	38.0	38.0	37.8	37.5	37.4	37.8	37.7	38.1	37.7	37.8	37.8	37.7
TiO_2		0.07		0.06				0.04	0.04	0.05	0.05		0.04	0.04
MnO	0.42	0.49	0.47	0.49	0.49	0.44	0.47	0.44	0.47	0.44	0.44	0.49	0.47	0.44
FeO	22.7	22.8	23.0	23.1	22.8	22.6	22.8	22.7	22.4	22.6	22.6	23.0	22.5	22.4
MgO	39.4	39.3	39.2	39.0	39.4	39.4	39.7	39.7	39.8	39.6	39.7	39.9	39.8	40.0
Total	100.2	101.0	100.6	100.6	100.4	99.9	100.4	100.6	100.4	100.8	100.5	101.1	100.6	100.7
Fa	24.5	24.6	24.7	24.9	24.5	24.4	24.3	24.3	24	24.2	24.2	24.4	24.1	23.9
SiO_2	37.7	37.9	37.7	37.5	38.1	37.9	37.4	37.1	37.5	37.1	37.8	37.0	37.4	37.4
TiO_2	0.04	0.06	0.04	0.06	0.04	0.05		0.06	0.04	0.05		0.06	0.05	
MnO	0.44	0.44	0.39	0.42	0.47	0.42	0.47	0.44	0.39	0.47	0.49	0.49	0.39	0.42
FeO	22.4	22.7	22.6	22.3	22.9	22.3	22.7	22.7	22.6	22.8	22.8	23.0	23.1	22.8
MgO	40.0	39.7	39.7	39.5	39.5	39.1	39.5	39.6	39.5	39.4	39.6	39.5	39.3	38.9
Total	100.7	100.8	100.4	99.9	101.0	99.9	100.1	99.9	100.1	99.9	100.8	100.1	100.2	99.5
Fa	23.9	24.3	24.2	24.1	24.5	24.2	24.4	24.3	24.2	24.5	24.4	24.6	24.8	24.7

monomict breccia with strongly re-crystallized texture. It consists mainly of chondrule fragments enclosed in a crystalline matrix. The matrix consists of tiny subhedral and anhedral crystals and opaque minerals intergrown with broken chondrules. The chondritic texture is poorly defined. Only a few chondrules (mainly radiating type, Fig. 1a) are visible. The essential minerals are olivine ($Fa_{24.4}$) and low-Ca pyroxene ($En_{77.8}$ $Fs_{20.7}$ $Wo_{1.6}$) (Tables 1, 2). Accessory minerals are plagioclase, Fe–Ni metal phases and polycrystalline troilite grains (Fig. 1b).

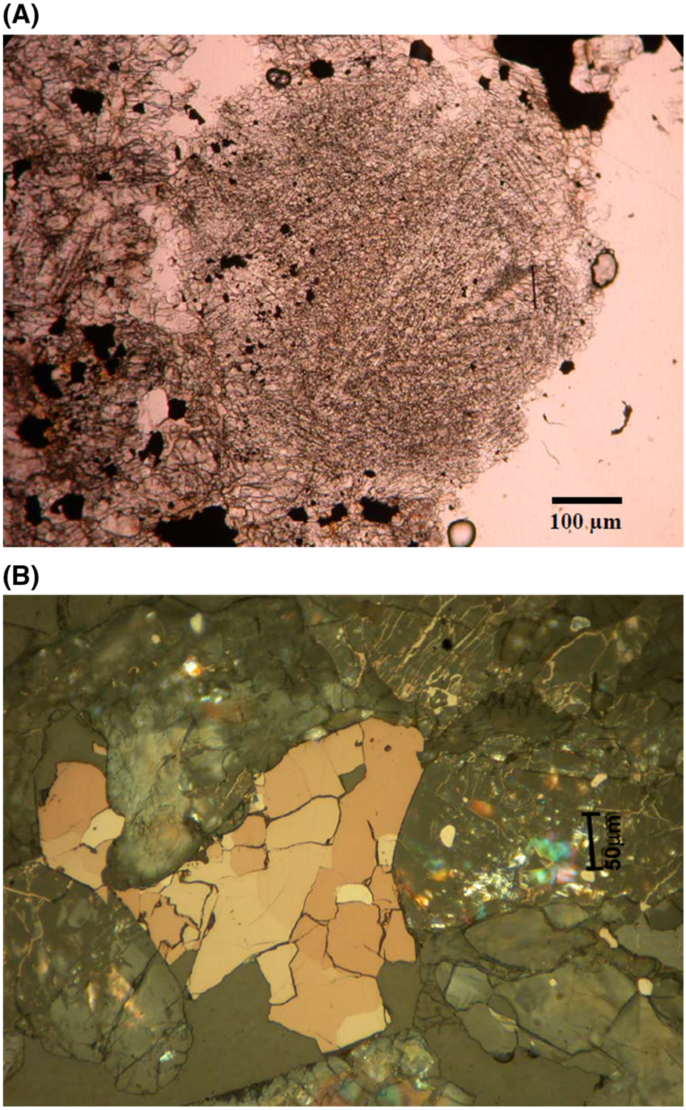

Fig. 1 **a** Photomicrographs in transmitted plane polarized light showing a radial chondrule in Santa Lucia (2008). **b** Photomicrographs in reflected light under XP showing the polycrystalline grains of troilite

Table 2 Representative EMP analysis of low-Ca pyroxene in Santa Lucia (2008)

												Mean
SiO_2	54.9	55.3	55.7	55.1	54.1	54.6	54.4	54.3	55.0	54.8	54.6	54.7	
Al_2O_3	0.25	0.15	0.12	0.12	0.09	0.11	0.04	0.04	0.04	0.04	0.05	0.05	
MnO	0.45	0.47	0.47	0.42	0.47	0.47	0.47	0.45	0.47	0.45	0.47	0.45	
FeO	14.0	13.8	14.1	14.1	13.8	14.3	14.2	14.2	14.1	14.0	14.0	14.0	
CaO	0.72	0.77	0.62	0.7	0.92	0.9	0.93	0.92	0.84	0.88	0.87	0.83	
TiO_2	0.18	0.19	0.18	0.21	0.17	0.19	0.11	0.15	0.12	0.1	0.11	0.11	
MgO	29.6	29.7	29.7	29.6	29.5	29.6	29.8	29.8	29.6	30.1	29.6	29.5	
Total	100.1	100.3	100.8	100.2	99.0	100.2	99.9	99.9	100.2	100.4	99.7	99.6	
En	78.0	78.2	78.1	77.8	77.9	77.4	77.5	77.5	77.6	78.0	77.8	77.7	77.8
Fs	20.7	20.3	20.7	20.8	20.4	21.0	20.7	20.8	20.8	20.4	20.6	20.7	20.7
Wo	1.4	1.5	1.2	1.3	1.7	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.6

Chemical data indicate that Santa Lucia (2008) is a member of the low iron L chondrite group (e.g., Brearley and Jones 1998). The observed texture and mineral phases led us to classify it as an equilibrated petrologic type 6 (Van Schmus and Wood 1967; Rubin 1990). The shock features of the minerals (e.g., undulatory extinction, planar structure) as well as the presence of twinned plagioclase and troilite occuring as polycrystalline grains suggest that the meteorite has been weakly shocked.

The bulk lithophile trace element abundance of Santa Luica (2008) is around chondritic ($1 - 2 \times$ CI) (Fig. 2a), showing also chondritic abundances for the siderophile Ir, Mo, Ni, Co, Fe, As, Au and Ag (Table 3).

3.2 Noble Gases and Nitrogen

The concentrations and isotopic ratios of the noble gases and nitrogen are given in Tables 4 and 5. The measured ^{20}Ne/^{22}Ne ratios (0.77–0.82) indicate that the Ne composition in

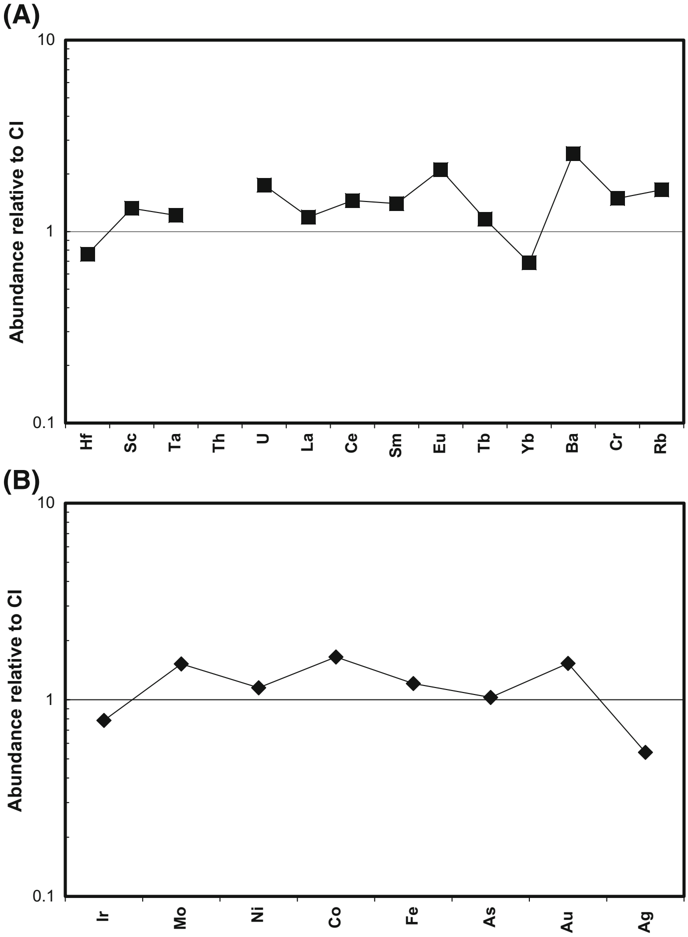

Fig. 2 CI-normalized (Lodders and Fegley 1998) trace element abundances of Santa Lucia (2008), **a** Litophile elements, **b** Siderophile elements

Table 3 Bulk trace element analysis (INAA)

	Abundante (ppm)	Error (±)
U	0.014	0.006
Th	0.02	0.01
Hf	0.08	0.04
Ta	0.017	0.008
Ba	6	3
Cs	0.023	0.01
Rb	3.8	0.9
Na (%)	1.06	0.01
Sb	0.1	0.02
Cr	3950	500
Co	833	10
Ni	12,650	450
Sc	7.8	0.1
Fe (%)	22.7	0.16
Zn	100	12
La	0.28	0.04
Ce	0.9	0.4
Sm	0.21	0.01
Eu	0.12	0.05
Tb	0.043	0.013
Yb	0.11	0.05
As	1.9	0.07
Mo	1.4	0.2
Au (ppb)	222	5
Ag (ppb)	108	9
Ir (ppb)	365	10

Santa Lucia (2008) is purely cosmogenic. There is no solar-wind gases. The measured $^{36}Ar/^{38}Ar$ and $^{40}Ar/^{36}Ar$ range between 1.8 to 0.97 and 4066 to 239 respectively, indicates the presence of cosmogenic, radiogenic and trapped components. The concentrations of cosmogenic, radiogenic and trapped components for noble gases and CRE ages are given in Table 6. Trapped He and Ne is negligible, small amounts of trapped ^{36}Ar, ^{84}Kr and ^{132}Xe are present, indicating carrier of trapped noble gases only contain Ar, Kr and Xe. As there is absence of solar-wind implanted noble gases, the radiogenic $^{4}He_r$ was calculated after subtracting the cosmogenic component. The measured ^{40}Ar concentration is taken entirely as radiogenic produce. Radiogenic ^{4}He and ^{40}Ar concentrations are 2.99×10^{-6} and 2.54×10^{-5} cm^3STP/g respectively. Using U and Th concentrations, 0.014 and 0.02 (Table 3), we obtain a U–Th–He age of 1.2 Ga. Using K = 850 ppm, concentration of chondrites (Wasson and Kallemeyn 1988), we obtain a K–Ar age of 2.96 Ga. These gas retention ages are lower than the crystallization ages of ordinary chondrites of about 4.5 Ga, and are due to gas loss during impact event on L chondrite parent body. Furthermore, the ratio $T_4/T_{40} = 0.4$ is less than unity, lower T_4 from T_{40} may be due the partial loss of radiogenic helium due to solar heating (Eugster et al. 1993). The measured $^{129}Xe/^{132}Xe = 1.169 \pm 0.050$ is similar to chondritic value, indicating presence of

Table 4 Measured Noble gas and nitrogen in Santa Lucia (2008)

Temperature	^{4}He	^{22}Ne	^{36}Ar	^{84}Kr	^{3}He/^{4}He	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar	^{82}Kr	^{83}Kr	^{86}Kr	N_2 ppm	δ^{15}N
	10^{-8} cm^{3}STP/g			10^{-12} ccSTP/g	10^{-5}					^{84}Kr ratio × 100				(‰)
600	61.76	0.15	0.14	b.l.	9574	0.7777	0.8781	0.7912	2324	b.l.	b.l.	b.l.	0.004	9.76
						±0.0006	0.0001	0.0018	1					0.16
1200	388.6	7.46	0.55	39	5868	0.8215	0.9403	0.5278	4066	23.802	22.984	29.429	0.364	17.32
						0.0001	0.0001	0.0008	7	0.029	0.054	0.159		0.10
1700	5.88	3.75	0.58	31	26,970	0.7919	0.9614	1.0288	239	23.583 0.048	23.200	29.781	0.536	17.21
						0.0001	0.0005	0.0003	1		0.159	0.159		0.11
Total	456.3	11.37	1.14	70	6641	0.8111	0.9467	0.7854	2102	23.705	23.080	29.585	0.904	17.22
						0.0001	0.0002	0.0006	3	0.038	0.100	0.126		0.11

Uncertainty is 10 % in concentrations

b. l. blank level

Table 5 Xenon in Santa Lucia (2008), ratios × 100

Temperature	^{132}Xe 10^{-12} cm^3STP/g	^{124}Xe/^{132}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
1200	36.37	0.529	0.740	8.470	119.8	16.264	82.817	38.489	30.881
		±0.016	0.007	0.013	0.4	0.086	0.172	0.378	0.051
1700	58.15	0.552	0.626	8.490	115.1	16.328	82.572	38.255	31.925
		0.001	0.001	0.041	7.8	0.115	0.034	0.030	0.062
Total	94.53	0.543	0.670	8.482	116.9	16.303	82.666	38.345	31.523
		0.007	0.003	0.030	5.0	0.104	0.087	0.164	0.058

radiogenic $^{129}Xe^*$ (from decay of ^{129}I). The radiogenic $^{129}Xe^*$ is 9.9×10^{-12} cm^3STP/g is small, indicating Xe retention temperature of the parent body attained late. The cosmogenic $(^{82}Kr/^{83}Kr)_c$ ratio estimated for Santa Lucia (2008) is 1.27, assuming Kr-Q as trapped composition (Busemann et al. 2000), is much higher that the pure spallation value expected for chondritic composition, 0.765 (Marti et al. 1966) suggest the presence of excess ^{82}Kr by neutron reaction, $^{81}Br(n, \gamma\beta)$ ^{82}Kr. In Fig. 3 where the ratio $^{82}Kr/^{84}Kr$ is plotted against $^{83}Kr/^{84}Kr$, the data points fall above the spallation-Q mixing line implies the excess in ^{82}Kr due to neutron reaction. The low $^{22}Ne/^{21}Ne$ cosmogenic ratio, 1.05 in Santa Lucia (2008) is indicative of deep shielding in large meteoroid. Both Ne and Kr suggest that the meteoroid was large enough to generate epithermal neutrons to produce $^{82}Kr_n$ (Göbel et al. 1982). However, the recovered mass is only ~6 kg, indicates major loss of mass due to ablation during fall. Xenon in Santa Lucia (2008) is mixture of Q and spallation. As shown in $^{124}Xe/^{132}Xe$ versus $^{136}Xe/^{132}Xe$ plot (Fig. 4) the data falls on Q and spallation mixing line. The elemental ratios $^{36}Ar/^{132}Xe = 67$ and $^{84}Kr/^{132}Xe = 0.73$ also indicates the presence of Q type trapped component (Busemann et al. 2000) typical for ordinary chondrites. The total nitrogen content in Santa Lucia (2008) is 0.9 ppm is within the range of ordinary chondrites (Sugiura et al. 1998) with $\delta^{15}N = 17.22 \pm 0.11$ ‰. The trapped nitrogen signature is $\delta^{15}N = 8.1$ after correcting the cosmogenic, using the cosmogenic production ratio of $(^{15}N/^{21}Ne)_c = 4.5$ for chondrites (Mathew and Murty 1993), is similar to nitrogen observed in ordinary chondrites (Suguira et al. 1998).

3.3 Cosmic-Ray Exposure History

We calculate the CRE ages from the cosmogenic ^3He, ^{21}Ne and ^{38}Ar concentrations and production rate methods of Marti and Graf (1992), which are independent of elemental composition. The 4π CRE ages obtained from ^3He_c, $^{21}Ne_c$ and $^{38}Ar_c$ are $T_3 = 18.4 \pm 0.2$, $T_{21} = 24.4 \pm 0.6$ and $T_{38} = 17.2 \pm 0.6$ Ma (Table 6). The average CRE age obtained from ^3He_c, $^{21}Ne_c$ and $^{38}Ar_c$ is 20.0 ± 0.9 Ma for Santa Lucia (2008). This CRE age, 20.0 Ma is consistent to the central peak of CRE age distribution of L chondrites (Alexeev 2005).

4 Conclusions

Santa Lucia (2008) consists of chemically homogeneous (in terms of Fe and Mg) major phases with chondritic bulk trace element abundances. Taking into account the average composition of olivine ($Fa_{24.4}$) and low-Ca pyroxene ($En_{77.8}$ $Fs_{20.7}$ $Wo_{1.6}$) this recent fall is

Table 6 Cosmogenic, radiogenic and trapped components in Santa Lucia (2008)

Cosmogenic								Radiogenic				Trapped		
^{3}He 10^{-8} ccSTP/g	^{21}Ne	^{38}Ar	$(^{22}Ne/^{21}Ne)_c$ Ma	T_3	T_{21}	T_{38}	$T_{average}$	^{4}He 10^{-5} ccSTP/g	^{40}Ar	T_4 Ga	T_{40}	^{36}Ar 10^{-12} ccSTP/g	^{84}Kr	^{132}Xe
30.3	10.78	0.78	1.05	18.5 ±0.6	24.4 ±0.6	17.2 ±0.1	20.0 ±0.9	29.9	2.41	1.2	2.96	6250	69	94

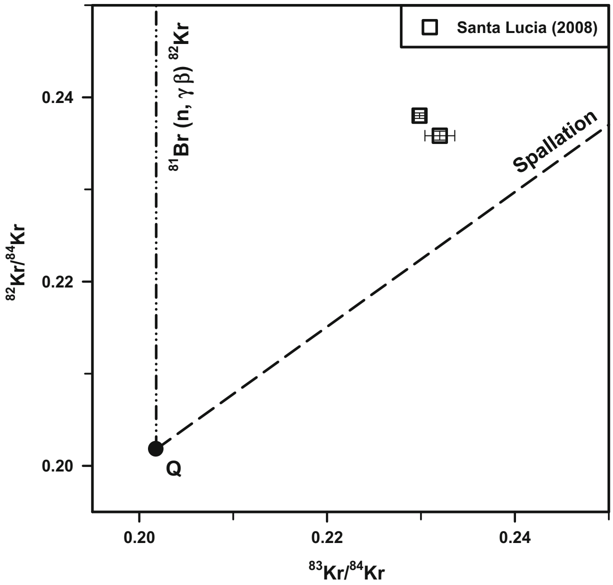

Fig. 3 Plot of $^{82}Kr/^{84}Kr$ against $^{83}Kr/^{84}Kr$. Trends expected for component mixture of Q (*trapped*) and spallation, and neutron produce are shown

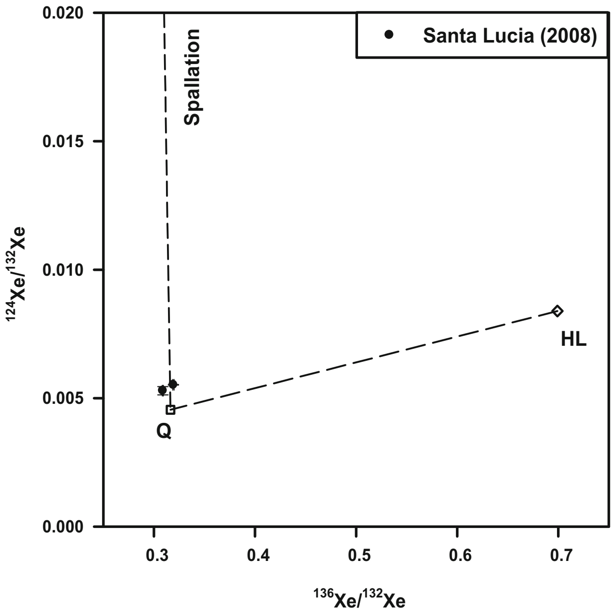

Fig. 4 Xenon $^{124}Xe/^{132}Xe$ versus $^{136}Xe/^{132}Xe$ three isotope plot of Santa Lucia (2008). Trapped component (Q) and trends of two component mixture, trapped and spallation and HL type are shown

thus classified as an equilibrated ordinary chondrite (L6) with a weak shock stage and a degree of weathering W0. The meteorite name was approved by the NomCom of the Meteoritical Society (Meteoritic Bulletin, no. 97).

Based on cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar, Santa Lucia (2008) shows a cosmic ray exposure (CRE) age around 20 Ma. The radiogenic K–Ar age is of 2.96 Ga, while the young U, Th–He are of 1.0 Ga suggesting that Santa Lucia (2008) lost radiogenic ^{4}He more recently. Our results show the absence of solar wind noble gases. Heavy noble gases (Ar/Kr/Xe) indicate presence of Q-type gases. Neon and krypton suggest large pre-atmospheric size of the meteoroid.

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