From D. News

'eteoritics & Planetary Science 33, 1335–1337 (1998)
Meteoritical Society, 1998. Printed in USA.

Report

The Campos Sales meteorite from Brazil: A lightly shocked L5 chondrite fall

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(Received 1998 April 8; accepted in revised form 1998 August 18)

Abstract–The Campos Sales meteorite fell close to the town of Campos Sales in the northeastern Brazilian state of Ceará (7°2' S, 40°10' W) on 1991 January 31 at 10:00 P.M. (local time). Several fragments were recovered from an area estimated to be 1 × 3 km. The stone is an ordinary L5 chondrite ($Fa_{25.0}$ and $Fs_{21.6}$) and is lightly shocked (S1). Metal phases present are kamacite, tetrataenite, and antitaenite. Noble gases He, Ne, Ar, Kr, and Xe have been analyzed in two bulk samples of Campos Sales. All exposure ages based on determination of cosmogenic ^{3}He, ^{21}Ne, ^{38}Ar, ^{83}Kr, and ^{126}Xe abundances and on the cosmogenic $^{81}Kr/^{83}Kr$ ratio agree well, which suggests no gas loss during cosmic-ray exposure. The cosmic-ray exposure age is 23.3 ± 1.0 Ma, which falls in the range observed for L5 chondrites (20–30 Ma). The gas-retention ages indicate He loss that must have occurred prior to or during ejection from the L-chondrite parent body.

INTRODUCTION

The Campos Sales meteorite fell close to a small town of the same name, situated in the northeastern Brazilian state of Ceará (7°2' S, 40°10' W) on 1991 January 31 at 10:00 P.M. (local time). The fall was observed by many local inhabitants and was accompanied by a loud buzzing noise and bright flash. Two of the authors (T. V. V. Costa and V. W. Vieira) arrived at the site of the fall 15 days later. Most observers reported astonishment by the fireball, the sonic boom, and the whizzing ("like the sound of bullets") of the falling stones.

Several fragments, spread over an area estimated to be 1 × 3 km, were recovered immediately after the fall by local people. Other small fragments (~200–300 g) were collected later by Costa and Vieira, near the road which crosses the grain field where many of the stones were picked up. A total of 23.68 kg of stones was recovered. All the fragments are now in the custody of Costa and Vieira at the Universidade Federal do Ceará.

From interviews with witnesses, it appears that the direction of the fireball's flight was from the southwest to the northeast, forming an estimated angle of trajectory of ~70° with the north-south direction. The size distribution of the fallen stones confirms this direction; the smaller stones fell west and the larger ones fell east, along the estimated direction of flight.

PETROGRAPHY

Campos Sales is a chondritic stony meteorite. Most of the fragments display large areas of thin, black fusion crust, with a slightly friable, light grey interior.

One polished and two covered thin sections, representing ~12 cm^2, have been used for petrographic and metallographic observations and microprobe analyses. There are many rather large chondrules; their sizes vary from 300 μm to 3 mm. In some areas, chondrules are broken and mixed with numerous mineral clasts; in others, they are clearly recognizable, though their outer limits are often indistinct except for olivine barred-chondrules, radial pyroxene chondrules, and fine-grained chondrules that are clearly delimited (Fig. 1).

No veins are present in these sections. Shock features are limited to numerous cracks in silicates and chromites, and Neumann bands in kamacite, which indicates that this chondrite was subjected to a low shock event (S1; Stöffler *et al.*, 1991). The usual variety of chondrules are represented; most of them are metal-free or have a low-metal and/or troilite content, but a few have troilite grains concentrated in their margin. A 2 mm-wide chondrule shows a core of silica—tridymite or cristobalite—with a large rim of intermixed Ca-poor and Ca-rich pyroxene, which is similar to the one described in the Nadiabondi chondrite (Christophe *et al.*, 1965). This chondrule occurs in a covered thin section, preventing microprobe analyses. A few chromite-rich objects are present: chromite is always accompanied by plagioclase feldspar and sometimes by olivine and by feldspar-chromite pseudomorphs on an unstable and, thus, unknown mineral (Christophe *et al.*, 1995).

Interchondrule phosphates (whitlockite and apatite) are monocrystalline in grains up to 300 μm across, in contrast to plagioclase feldspar areas that are polycrystalline with grains <50 μm.

CHEMISTRY AND MINERALOGY

Electron microprobe analyses (Table 1) show that olivine gives a mean of $Fa_{25.0}$ (24.7–25.2) with CaO ≤ 0.02%. Pyroxenes are $Fs_{21.6}$ (20.9–22.3) with $Wo_{1.6}$ (1.4–1.9). Two analyses of chromite

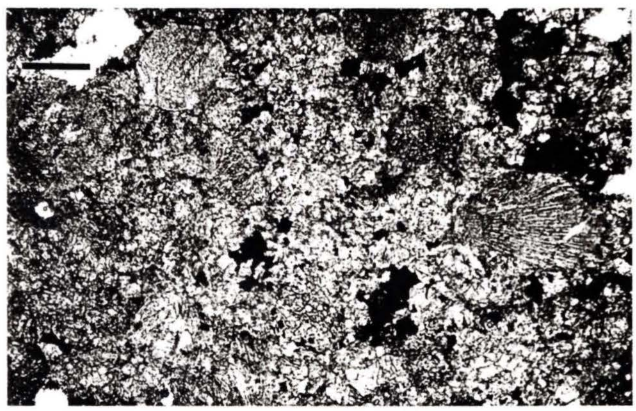

FIG. 1. Optical micrograph showing a global view by transmission of the Campos Sales L5 chondrite. Scale bar is 1 mm.

TABLE 1. Representative mineral analyses.

	Ol	Px	Cr
SiO_2	38.30	55.85	0.00
TiO_2	0.02	0.18	3.09
Al_2O_3	0.01	0.14	5.64
Cr_2O_3	0.00	0.19	56.73
FeO	22.47	13.58	28.56
Fe_2O_3	n.d.	n.d.	2.62
MnO	0.42	0.42	0.71
MgO	39.11	28.97	2.24
CaO	0.02	0.98	0.04
Total	100.34	100.31	99.15
	$Fa_{25.0}$	$Fs_{21.6}$ $Wo_{1.9}$	

Ol = olivine; Px = pyroxene; Cr = chromite.
n.d. = below detection.

give $(Mg_{0.98}Fe_{6.90}Mn_{0.17})(Al_{1.88}Cr_{12.60}Ti_{0.66}Fe_{0.46})O_{32}$ (V was not measured). The olivine and pyroxene data are in agreement with those of equilibrated L chondrites (Bunch *et al.*, 1967).

Kamacite contains 6.2–6.5% Ni and 0.4–0.7% Co; whereas in Ni-rich taenite, Co is under the detection limit. Rare tiny Cu blebs are found near tetrataenite and troilite. Native Cu is a common trace phase in many ordinary chondrites (Rubin, 1994).

The textural features together with the mineralogical (occurrence of both ortho- and striated pyroxenes, presence of plagioclase grains, and homogeneity of the silicates) and chemical characteristics of the Campos Sales chondrite allow its classification as a lightly shocked L5 chondrite (Van Schmus *et al.*, 1967).

NOBLE GASES

Helium, Neon, and Argon Analyses

We report in Table 2 the concentrations and isotopic ratios of He, Ne, and Ar measured in a 66.5 mg sample of Campos Sales. From these data, and using standard assumptions made for the isotopic ratios (see Eugster *et al.*, 1993), the cosmogenic and radiogenic components are determined and the inferred gas-retention ages are given in Table 3. Radiogenic ages are calculated adopting 0.013 μg/g U, 0.043 μg/g Th (Wasson and Kallemeyn, 1988), and 858 μg/g K (Kallemeyn *et al.*, 1989). No ^{40}Ar loss is evident, based on the T_{40} age. On the other hand, T_4 suggests high He loss that must have occurred prior to or during ejection from the L-chondrite parent body.

Krypton and Xenon Analyses

Concentrations and isotopic ratios of Kr and Xe were measured in 1.125 g of bulk sample. Results given in Table 2 are for gases extracted during melting of the sample at 1800 °C. An initial 500 °C temperature step released noble gases with an atmospheric composition and was discarded. Abundances of cosmogenic Kr and Xe isotopes are presented in Table 3 as well as fissionogenic ^{136}Xe concentration. Partitioning of the cosmogenic, trapped, and fissionogenic components is determined following assumptions given in Lavielle *et al.* (1997). Fissionogenic ^{136}Xe concentration is

TABLE 2. Measured concentrations (cm^3 STP/g) and isotopic ratios in Campos Sales.

^{4}He	^{21}Ne	^{38}Ar	^{3}He	^{20}Ne	^{22}Ne	^{36}Ar	^{40}Ar
	(10^{-8})		^{4}He	$^{21}Ne = 1$		$^{38}Ar = 1$	
1094 ±40	7.76 ±0.32	1.059 ±0.074	0.0344 ±0.0008	0.9297 ±0.0068	1.1116 ±0.0088	1.025 ±0.060	6601 ±540

^{86}Kr	^{78}Kr	^{80}Kr	^{81}Kr	^{82}Kr	^{83}Kr	^{84}Kr
(10^{-12})	$^{86}Kr = 1$					
24.0 ±2.0	0.0443 ±0.0024	0.2009 ±0.0042	0.00114 ±0.00030	0.7591 ±0.0092	0.7867 ±0.0091	3.323 ±0.026

^{136}Xe	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe
(10^{-12})	$^{136}Xe = 1$							
28.1 ±2.8	0.01753 ±0.00020	0.01865 ±0.00018	0.2591 ±0.0016	3.642 ±0.017	0.5002 ±0.0022	2.503 ±0.010	3.077 ±0.010	1.1859 ±0.0029

Experimental errors are 2σ.

TABLE 3. Cosmogenic and radiogenic concentrations (cm^3 STP/g) and ages (Ma) in Campos Sales.

	Cosmogenic							Radiogenic		
	^{3}He	^{21}Ne	^{38}Ar	^{83}Kr	^{126}Xe	^{81}Kr	^{22}Ne	^{4}He*	^{40}Ar	^{136}Xe
		(10^{-8})		(10^{-12})		^{83}Kr	^{21}Ne	(10^{-8})		(10^{-12})
Conc.	37.7 ±1.5	7.75 ±0.32	0.974 ±0.068	3.18 ±0.34	0.171 ±0.020	0.0083 ±0.0024	1.1065 ±0.0098	898 ±35	6990 ±600	0.88 ±0.62
Age	23.4 ±1.7	23.0 ±1.7	23.1 ±2.5	25.3 ±3.9	24.4 ±3.8	21.9 ±6.7		2623 ±85	4595 ±151	

*Assuming no trapped ^{4}He. Errors are 2σ.

calculated after subtraction of ^{136}Xe from ^{238}U spontaneous fission produced in 4500 Ma. A correction applied to ^{81}Kr, for ^{81}Br and hydrocarbon contributions, represents ~15% of the measured signal.

Exposure Age

Exposure ages are obtained from cosmogenic ^{3}He, ^{21}Ne, ^{38}Ar, ^{83}Kr, and ^{126}Xe concentrations and from the cosmogenic ratio of $^{81}Kr/^{83}Kr$ using production rate calibrations proposed by Eugster (1988) and by Marti and Graf (1992). All ages agree within uncertainties (Table 3), which suggests no gas loss during exposure time. A weighted average of 23.3 ± 1.0 Ma is derived that falls in the cluster, pointed out by Marti and Graf (1992) for the L chondrites, at 20–30 Ma as shown in Fig. 2.

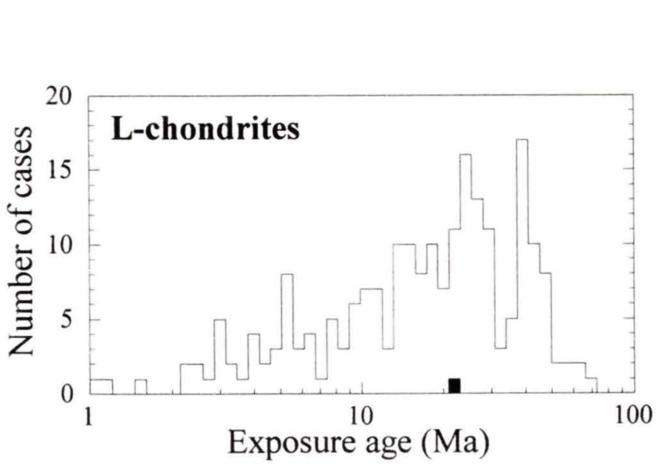

FIG. 2. Distribution of L-chondrite cosmic-ray exposure ages after Marti and Graf (1992). Campos Sales falls in the cluster at 20–30 Ma.

METAL

Iron-57 Mössbauer spectroscopy of a bulk sample of the Campos Sales chondrite revealed only the presence of troilite and silicates; metal phases could not be detected. Analysis of the Mössbauer spectrum of a separated metal fraction (after chemical treatment) indicated the presence of Ni-rich and Ni-poor taenite phases, showing the typical intergrowth of tetrataenite (ordered $Fe_{50}Ni_{50}$) and the γ-low spin phase (γ_{LS}) with Ni <30% (Rancourt and Scorzelli, 1995). Tetrataenite comprises ~20% of the total relative area of the spectrum, with hyperfine parameters typical of a well-ordered and low-shocked chondrite (quadrupole splitting ΔE_Q = 0.20 mm/s and internal magnetic field H_i = 29T). The relative proportion of the γ_{LS} phase is ~10%, and the remaining spectrum area (70%) corresponds to the presence of kamacite.

The presence of the intergrowth tetrataenite/γ_{LS} as well as the hyperfine parameters of tetrataenite is an indication that this meteorite was slowly cooled and could not have suffered more than slight shock, which is in agreement with optical observations.

Acknowledgments–We are grateful to the CNPq for the support given for the study of meteorites. Part of this work was supported by C.N.R.S., I.N.S.U. (Programme National de Planétologie) and the University of Bordeaux I.

Editorial handling: D. W. Mittlefehldt

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