

Report

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

R. B. SCORZELLI¹, M. CHRISTOPHE MICHEL-LÉVY², E. GILABERT³, B. LAVIELLE³,
 I. SOUZA AZEVEDO¹, V. W. VIEIRA⁴, T. V. V. COSTA⁴ AND M. A. B. ARAÚJO⁴

¹Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, 22290-180, Rio de Janeiro, Brazil

²Laboratoire Minéralogie-Cristallographie, Université Pierre et Marie Curie, 4 Place Jussieu, Paris VI, France

³URA 451 CNRS, Le Haut Vigneau, BP120, 33175 Gradignan Cedex, France

⁴Departamento de Física, Universidade Federal do Ceará, 60451-970 Fortaleza, Brazil

*Correspondence author's e-mail address: scorza@cat.cbpf.br

(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, tetraenaite, 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 ³He, ²¹Ne, ³⁸Ar, ⁸³Kr, and ¹²⁶Xe abundances and on the cosmogenic ⁸¹Kr/⁸³Kr 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 cm², 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

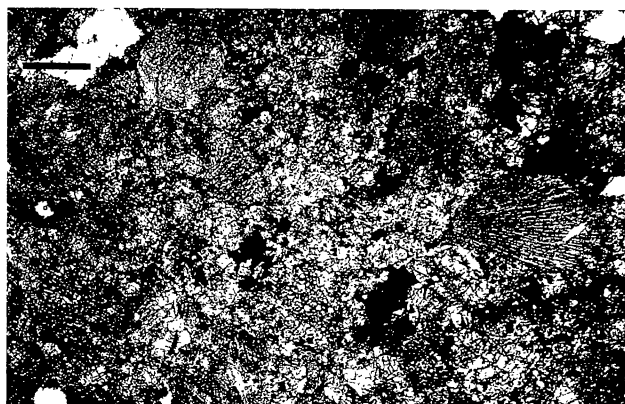


FIG. 1. Optical micrograph showing a global view by transmission of the Campos Sales L5 chondrite. Scale bar is 1 mm.

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 ₂ O ₃	0.01	0.14	5.64
Cr ₂ O ₃	0.00	0.19	56.73
FeO	22.47	13.58	28.56
Fe ₂ O 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})O₃₂ (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 $\mu\text{g/g}$ U, 0.043 $\mu\text{g/g}$ Th (Wasson and Kallemeyn, 1988), and 858 $\mu\text{g/g}$ K (Kallemeyn *et al.*, 1989). No ⁴⁰Ar loss is evident, based on the T₄₀ age. On the other hand, T₄ 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 ¹³⁶Xe concentration. Partitioning of the cosmogenic, trapped, and fissionogenic components is determined following assumptions given in Lavielle *et al.* (1997). Fissionogenic ¹³⁶Xe concentration is

TABLE 2. Measured concentrations (cm³ 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		
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
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 2 σ .

TABLE 3. Cosmogenic and radiogenic concentrations (cm³ 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 ⁴He. Errors are 2 σ .

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 $\sim 15\%$ of the measured signal.

Exposure Age

Exposure ages are obtained from cosmogenic ^3He , ^{21}Ne , ^{38}Ar , ^{83}Kr , and ^{126}Xe concentrations and from the cosmogenic ratio of $^{81}\text{Kr}/^{83}\text{Kr}$ 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.

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 $\text{Fe}_{50}\text{Ni}_{50}$) and the γ -low spin phase (γ_{LS}) with Ni $< 30\%$ (Rancourt and Scorzelli, 1995). Tetrataenite comprises $\sim 20\%$ of the total relative area of the spectrum, with hyperfine parameters typical of a well-ordered and low-shocked chondrite (quadrupole splitting $\Delta E_{\text{Q}} = 0.20$ mm/s and internal magnetic field $H_i = 29\text{T}$). The relative proportion of the γ_{LS} phase is $\sim 10\%$, 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

REFERENCES

- BUNCH T. E., KEIL K. AND SNETTSINGER K. G. (1967) Chromite composition in relation to chemistry and texture of ordinary chondrites. *Geochim. Cosmochim. Acta* **31**, 1569–1582.
- CHRISTOPHE MICHEL-LÉVY M., CURIEN H. AND GONI J. (1965) Etude à la microsonde électronique d'un chondre d'olivine en barre et d'un fragment riche en cristobalite de la météorite Nadiabondi. *Bull. Soc. Franc. Miner. Crist.* **88**, 122–125.

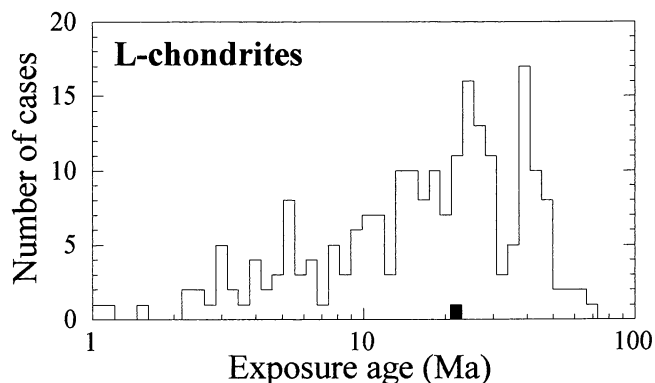


FIG. 2. Distribution of L-chondrite cosmic-ray exposure ages after Marti and Graf (1992). Campos Sales falls in the cluster at 20–30 Ma.

- CHRISTOPHE MICHEL-LÉVY M., ROBIN E. AND BLANC P. H. (1995) Occurrence of noble metals in aluminum- and chromium-rich objects in ordinary chondrites and of baddeleyite (ZrO_2) in a chromite inclusion. *Meteoritics* **30**, 15–19.
- EUGSTER O. (1988) Cosmic-ray production rates for ^3He , ^{21}Ne , ^{38}Ar , ^{83}Kr , and ^{126}Xe in chondrites based on ^{81}Kr -Kr exposure ages. *Geochim. Cosmochim. Acta* **52**, 1649–1662.
- EUGSTER O., MICHEL TH., NIEDERMANN S., WANG D. AND YI W. (1993) The record of cosmogenic, radiogenic, fissionogenic, and trapped noble gases in recently recovered Chinese and other chondrites. *Geochim. Cosmochim. Acta* **57**, 1115–1142.
- KALLEMEYN G. W., RUBIN A. E., WANG D. AND WASSON J. T. (1989) Ordinary chondrites: Bulk compositions, classification, lithophile-element fractionations, and composition-petrographic type relationships. *Geochim. Cosmochim. Acta* **53**, 2747–2765.
- LAVIELLE B., TOE S. AND GILBERT E. (1997) Noble gas measurements in the L/LL5 chondrite Knyahinya. *Meteorit. Planet. Sci.* **32**, 97–107.
- MARTI K. AND GRAF T. (1992) Cosmic-ray exposure history of ordinary chondrites. *Annu. Rev. Earth Planet. Sci.* **20**, 221–243.
- RANCOURT D. G. AND SCORZELLI R. B. (1995) Low-spin γ -Fe-Ni (γ_{LS}) proposed as a new mineral in Fe-Ni bearing meteorites: Epitaxial intergrowth of γ_{LS} and tetrataenite as a possible equilibrium state at ~ 20 –40 at% Ni. *J. Magn. Magn. Mat.* **150**, 30–36.
- RUBIN A. E. (1994) Metallic copper in ordinary chondrites. *Meteoritics* **29**, 93–99.
- STÖFFLER D., KEIL K. AND SCOTT E. R. D. (1991) Shock metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta* **55**, 3845–3867.
- VAN SCHMUS W. R. AND WOOD J. A. (1967) A chemical-petrologic classification for the chondritic meteorites. *Geochim. Cosmochim. Acta* **31**, 747–765.
- WASSON J. T. AND KALLEMEYN G. W. (1988) Compositions of chondrites. *Phil. Trans. Royal Soc. London A* **325**, 535–544.