

PRIMORDIAL COMPOSITIONS OF REFRACTORY INCLUSIONS. L. Grossman^{1,2}, S. B. Simon¹, V. K. Rai³, M. H. Thiemens³, I. D. Hutcheon⁴, R. W. Williams⁴, A. Galy⁵, T. Ding⁶, R. N. Clayton^{1,2} and T. K. Mayeda².
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Introduction: Grossman et al. [1] suggested that Types A and B refractory inclusions from CV3 chondrites are evaporation residues of high-temperature condensate assemblages, based on the deviation of the bulk MgO and SiO₂ contents of inclusions from those predicted by theoretical calculations for refractory condensate assemblages, and from their measured enrichments in the heavy isotopes of Mg and Si. Although the magnitudes of the deviations of the MgO and SiO₂ contents of the objects in that study are generally consistent with the degree of evaporation inferred from the Mg and Si isotopic mass-fractionations measured in similar objects, determination of a set of primordial, *i.e.* pre-evaporation, compositions of refractory inclusions must be based on correcting the bulk chemical composition of each object for the degree of Mg and Si evaporation experienced by the same object. This requires that a measurement of the bulk chemical composition, a bulk Mg isotopic composition and a bulk Si isotopic composition be performed on each member of a suite of inclusions. Such a study was begun and the bulk Mg isotopic data reported in [2]. Here we report new bulk oxygen and silicon isotopic compositions for the same inclusions, and infer their primordial compositions.

Sampling and analytical techniques: Sampling, bulk chemical, and Mg isotopic techniques are given in [2]. Bulk O-isotopic compositions were determined after fluorination following the procedure of [3]. SiF₄ was extracted and the Si isotopic compositions determined with a MAT-253 gas source isotope ratio mass spectrometer [4, 5]. A 9.12 kV accelerating voltage was used with a magnetic field intensity of 0.9509T. The masses 85, 86 and 87 were collected simultaneously and the results are expressed as $\delta^{29}\text{Si}$ and $\delta^{30}\text{Si}$ values relative to NBS-28.

Results: Data obtained for this study, supplemented by some published values, are given in Table 1. The (“observed”) bulk compositions have been normalized to 100 wt% CMAS and corrected to the solar CaO/Al₂O₃ ratio [6]. Our largest source of error is in the determination of bulk chemical compositions of the inclusions. For a given section of an inclusion, modal recombination gives a robust result, but its value is dependent upon the representativeness of the section.

The silicon isotopic compositions plot along a mass-dependent fractionation curve, and oxygen isotopic compositions plot along the CCAM line, showing that they are all normal, non-FUN inclusions. Positive F_{Si} and F_{Mg} values (degrees of enrichment in heavy isotopes relative to solar system values) were taken to reflect losses of those elements by evaporation. Experimentally determined isotopic fractionation factors for CAI compositions, 0.98797 for Mg and 0.9898 for Si [7], were used. Assuming the CAIs had normal Mg and Si isotopic compositions before evaporation, underwent Rayleigh distillation at a constant temperature of 1500°C as homogeneous liquids before significant crystallization began and experienced no recondensation, the resulting evaporative losses are 12-50% Mg and 5-24% Si, except for Vigarano CAI 1623-8 (59%, 40%). The corresponding amounts of MgO and SiO₂ lost were added to the observed compositions (given in Table 1), and renormalized to give “original” bulk compositions consistent with the degrees of evaporation indicated by the isotopic compositions.

Observed and original compositions are plotted in Fig. 1 (Type As) and Fig. 2 (Type Bs). Arrows connect the original compositions (OR; open symbols) to the observed (OB; filled symbols) ones. The different orientations of these arrows reflect different fractional losses of Mg relative to Si. They suggest a wide range of physico-chemical conditions during evaporation, as the relative amounts of Si and Mg evaporated can depend on initial bulk composition, temperature, and the fraction of either element evaporated.

A calculated trajectory of bulk condensate compositions from a solar gas at $P^{\text{tot}}=10^{-5}$ bar is shown for reference. Trajectories for other conditions are different. The original compositions scatter about the condensate trajectory but do not define a trend consistent with a single set of physico-chemical conditions. Of the 14 original compositions plotted, half plot closer to the trajectory than the final compositions, four are further, and three are about the same distance from the trajectory as the observed compositions. Either the inclusions represent condensates from many different trajectories, or perhaps they are assemblages that formed by non-representative sampling (in the nebula) of condensate minerals from a single trajectory.

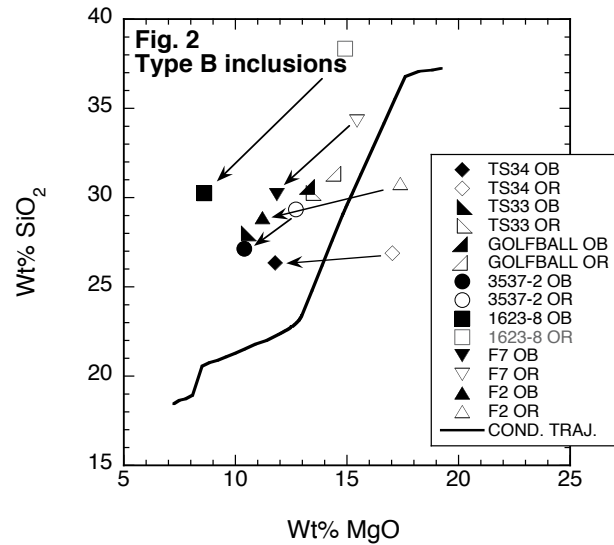
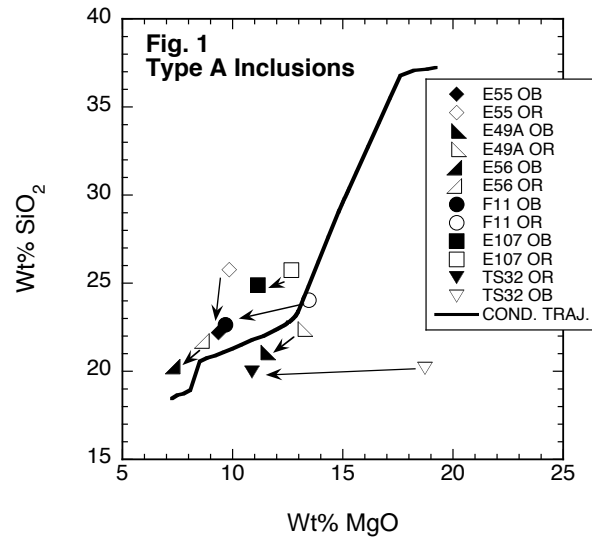


Fig. 2. Plot of Wt% SiO₂ vs. Wt% MgO in measured (Observed) and calculated (Original) bulk compositions of Type B CAIs. TS34, TS33 and 3537-2 are B1s.

Fig. 1. Plot of Wt% SiO₂ vs. Wt% MgO in measured (Observed) and calculated (Original) bulk compositions of Type A CAIs.

References: [1] Grossman L. et al. (2000) *GCA*, 64, 2879–2894. [2] Simon S. B. et al. (2004) *LPS XXXV*, Abstract #1684. *Meteoritics & Planet. Sci.*, 32, A74. [3] Clayton R. N. et al. (1976) *EPSL*, 30, 10-18. [4]

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Table 1. Bulk chemical and isotopic compositions of refractory inclusions. CTA: Compact Type A. Fo-B: Forsterite-bearing. Meth.: Method. MR: Modal Recombination. INAA: Instrumental neutron activation analysis. Typical uncertainties are ~0.05‰/amu for Si and <0.1‰/amu for O. ¹From [2]. ²From [8]. ³This study. ⁴From [9].

Meteorite	Sample	Type	CaO	MgO	Al ₂ O ₃	SiO ₂	Meth.	F _{Mg}	F _{Si}	δ ¹⁸ O	δ ¹⁷ O
Allende	TS32	CTA	30.56	10.88	38.60	19.95	MR	8.05±0.50 ¹	1.26	-7.3	-11
Allende	TS33	B1	27.18	10.49	34.34	28.00	MR	4.01±0.04 ¹	1.41	-19.4	-21.5
Allende	TS34	B1	27.34	11.79	34.53	26.34	MR	5.63±0.28 ¹	0.94	-16.7	-19.4
Allende	F2 (TS65)	B2	26.47	11.22	33.43	28.88	MR	6.12±0.03 ¹	1.85	-23.3	-27.5
Allende	F7 (TS67)	B2	25.62	11.86	32.36	30.16	MR	4.9±0.6 ²	1.49	-16.1	-19.8
Allende	F11 (TS68)	CTA	29.91	9.68	37.78	22.64	MR	4.9±1.3 ²	1.15	-6.6	-10.3
Allende	GOLFBALL	B	24.79	13.32	31.31	30.59	MR	1.61±0.06 ¹	0.25	-22.1	-25.7
Efremovka	E13	CTA	26.85	9.38	33.91	29.87	INAA	-1.03±0.07 ¹	-0.51	-34.5	-37.4
Efremovka	E49A	CTA	29.79	11.52	37.62	21.07	INAA	2.17±0.05 ¹	0.81	-3.1	-8.6
Efremovka	E49	CTA						5.41±0.07 ¹	1.2	-1	-6.5
Efremovka	E55	CTA	30.24	9.36	38.20	22.19	INAA	1.35±0.23 ¹	1.87	-4.4	-7.4
Efremovka	E56	CTA	31.94	7.39	40.40	20.27	MR	2.45±0.11 ¹	0.83	-7.2	-10.7
Efremovka	E60	Fo-B	21.06	18.64	26.61	33.69	INAA	3.78±0.08 ³	1.46	-21.1	-24.8
Efremovka	E62	CTA	32.61	6.47	41.18	19.74	INAA	-1.25±0.11 ¹	2.71	-7.9	-12.4
Efremovka	E107	A/B	28.26	11.15	35.70	24.89	MR	1.99±0.06 ¹	0.46	-10.2	-14.4
Leoville	3537-2	B1	27.60	10.40	34.86	27.14	MR	3.26±0.14 ¹	1.28	-23.1	-27.3
Vigarano	1623-8	B2	27.04	8.61	34.11	30.25	MR	9.9±0.5 ⁴	4.9	-17.1	-21.4