

**INAA OF CAIS FROM THE MARALINGA CK4 CHONDRITE: EFFECTS OF PARENT BODY THERMAL METAMORPHISM;** D. J. Lindstrom<sup>1</sup>, L.P. Keller<sup>1</sup>, and R. R. Martinez<sup>2</sup>. <sup>1</sup>SN4, NASA/JSC, Houston TX 77058; <sup>2</sup>C23 LESC, 2400 NASA Road 1, Houston, TX 77058.

Maralinga is an anomalous CK4 carbonaceous chondrite which contains numerous Ca-, Al-rich inclusions (CAIs) unlike the other members of the CK group [1]. These CAIs are characterized by abundant green hercynitic spinel intergrown with plagioclase and high-Ca clinopyroxene, and a total lack of melilite [2]. We have used Instrumental Neutron Activation Analysis (INAA) to further characterize the meteorite, with special focus on the CAIs. High sensitivity INAA [3] was done on eight sample disks about 100-150  $\mu\text{m}$  in diameter obtained from a normal 30  $\mu\text{m}$  thin section with a diamond microcoring device [4]. The CAIs are enriched by 60-70X bulk meteorite values in Zn, suggesting that the substantial exchange of Fe for Mg that made the spinel in the CAIs hercynitic also allowed efficient scavenging of Zn from the rest of the meteorite during parent body thermal metamorphism. Less mobile elements appear to have maintained their initial heterogeneity.

Analytical. Because the samples are too small to weigh accurately (0.1-1.2  $\mu\text{g}$ ), their masses have been estimated from the measured amounts of Fe and estimates of FeO content from microprobe work [1,4]. Thus, absolute abundances are uncertain by about  $\pm 10\%$ , but elemental ratios for well-determined elements are more accurate. The low abundances of many interesting trace elements in chondritic meteorites make them less than ideal subjects for INAA even when abundant material is available, and the two sigma upper limits for a number of elements under the conditions used here were less than chondritic values. Nonetheless, positive compositional anomalies would have been readily visible even for some unfavorable elements, and the "good" INAA elements offer some interesting insights. This was essentially a feasibility study of a few drilled samples, and would benefit from microprobe analyses of the specific areas sampled.

Results. The disk drilled from one of the two spinel-rich inclusions broke into three pieces (about 0.6, 0.3, and 0.3  $\mu\text{g}$ ) which were analyzed separately. Considerable variations in composition are apparent (see Table), with the largest variations observed in Sc (8X), Ir (25X) and Au (about 6X). The sample highest in Ir (about 3 ppm) had the lowest Au value (20 ppb). Refractory metals (including Re and Rh, which were observed but not quantified) show considerable variability at this scale, presumably reflecting trace sulfides, etc. [5]. Sm, the only rare earth element detected in all three aliquots, varied by a factor of 3, as did Na, while Cr, Co, Ni, and Zn varied by about 30% from highest to lowest. The other green spinel inclusion has similar contents of transition metals and somewhat higher contents of rare earths, Ca, and K. The most striking compositional feature of these green inclusions is their very high Zn contents (2930-5510 ppm, averaging about 4000 ppm). Also analyzed were a sample of matrix, a variety of chondrules and other inclusions, a large magnetite grain, and a sample of a hydrated iron oxide weathering vein. The matrix sample resembles previous bulk analyses of Maralinga [6,7], but is slightly lower in Fe, Cr, Co, and Ni (perhaps in part due to normalization to the fairly low matrix FeO value determined by defocused electron beam analysis [1]), and higher in Na. The Sc content of the matrix sample is only about half the bulk value, and may simply represent sampling of matrix in a low-Sc region distant from any high-Sc inclusions. Another curious feature of the matrix analysis is  $4.3 \pm 0.6$  ppm tungsten, presumably due to sampling of a region once containing tungsten-rich minerals. Three textural varieties of olivine-rich chondrules were sampled, and their analyses are unremarkable, except that one has quite high Sc.

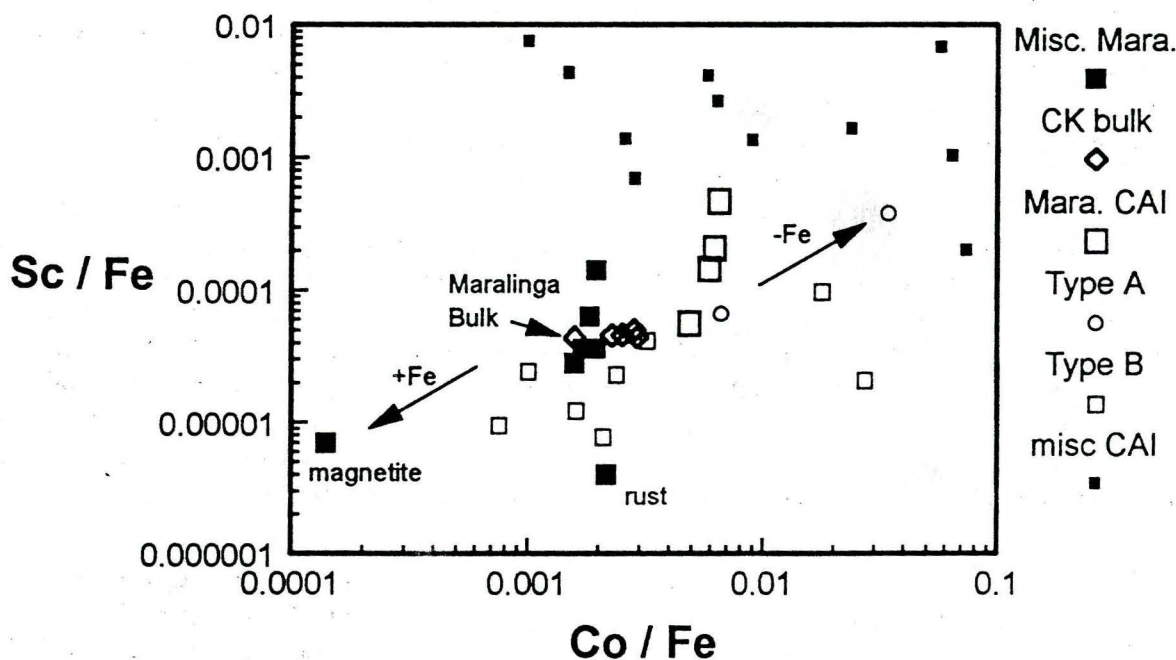
Discussion. Variability in Sc (note the vertical trends in the figure) may be simply a problem in sampling the clinopyroxene that is the phase richest in Sc, or may mean that inhomogeneities arising from high-Sc CAIs have not been fully erased during metamorphism. The 4000 ppm average Zn content of the CAIs is 40X the average CK chondrite value [6], and 60-70X the bulk Maralinga value of 65 [7] or 57 ppm [6]. If all the Zn in the meteorite were in the green inclusions, they could comprise no more than  $\sim 1.5\%$  of the

INAA OF CAIS IN MARALINGA: Lindstrom D. J. et al.

sample, a value which is in surprisingly good agreement with the estimated abundance of CAIs obtained using the petrographic microscope [1]. Of course, substantial amounts of Zn are also observed in our matrix and chondrule analyses, and it is quite possible that the aliquots from which the bulk samples were taken were poor in CAIs. Still, the Zn enrichment in spinel is remarkable. Volatile Zn should have been absent from the original CAIs, and must have been transported efficiently from a sizable volume of meteorite in order to attain the levels observed. Homogeneous olivine compositions throughout the meteorite attest to the efficiency of redistribution of divalent Mg, Fe, and Ni. Also, matrix plagioclase grains are strongly zoned, with ~An<sub>80</sub> rims surrounding cores of ~An<sub>40</sub>, suggesting that extensive Ca diffusion occurred during thermal metamorphism [8]. Additional petrographic evidence of Ca diffusion is the replacement of perovskite by ilmenite in several of the inclusions. Thus, redistribution of Zn is to be expected. Less mobile species such as Al and Si could not have moved substantially without obliterating much of the texture. Perhaps other more highly charged species such as Sc have also experienced limited mobility, and could help explain the small-scale variability observed in this work.

References: [1] Keller L.P., Clark J. C., Lewis C. F., and Moore C. B. (1992) *Meteoritics* 27, 87-91. [2] Keller L. P. (1992) LPSC XXIII, 671-2. [3] Lindstrom D. J. (1990) *Nucl. Instr. Meth. Phys Res. A299*, 584-588. [4] Ulrike Medenbach, Bruno-Heide Strasse 8, D-5810 Witten 3, Germany. [5] Geiger T. and Bischoff A. (1989) LPSC XX, 335-336. [6] Kallemeyn G. W., Rubin A. E., and Wasson J. T. (1991) *GCA* 55, 881-892. [7] Geiger T. and Spettel B. (1991) LPSC XXII, 133-4. [8] Keller L.P. (1993), this volume.

	CALCIUM-, ALUMINUM-RICH INCLUSIONS				MATRIX	CHONDRULES			
	A1	A2	A3	B		olivine	fine grained	barred	
	0.60 ug.	0.28 ug.	0.30 ug.	0.76 ug.	0.44 ug.	0.43 ug.	0.16 ug.	1.09 ug.	
Na2O	0.1050 ± 0.0018	0.200 ± 0.003	0.442 ± 0.007	0.347 ± 0.005	0.420 ± 0.007	0.0387 ± 0.0008	0.0867 ± 0.0016	0.258 ± 0.004	Na2O
FeO	15.01 ± 0.18	15.05 ± 0.20	15.01 ± 0.19	15.03 ± 0.18	27.0 ± 0.3	30.1 ± 0.3	29.9 ± 0.4	30.2 ± 0.3	FeO
Sc	6.58 ± 0.09	16.9 ± 0.2	54.0 ± 0.6	23.3 ± 0.3	5.83 ± 0.09	8.40 ± 0.11	8.44 ± 0.13	33.2 ± 0.4	Sc
Cr	2800. ± 40.	1980. ± 30.	2130. ± 30.	2640. ± 40.	2820. ± 40.	1169. ± 16.	1910. ± 30.	2400. ± 30.	Cr
Co	564. ± 7.	689. ± 8.	747. ± 9.	725. ± 9.	332. ± 4.	456. ± 5.	397. ± 5.	457. ± 5.	Co
Ni	3710. ± 70.	4530. ± 130.	5040. ± 130.	4450. ± 90.	3490. ± 90.	4800. ± 100.	3760. ± 140.	4920. ± 90.	Ni
Sm	0.097 ± 0.013	0.178 ± 0.017	0.32 ± 0.03	0.388 ± 0.017	0.132 ± 0.018	0.210 ± 0.011	0.096 ± 0.012	0.485 ± 0.014	Sm
Ir	0.120 ± 0.014	3.2 ± 0.3	0.112 ± 0.015	4.2 ± 0.4	0.137 ± 0.016	0.31 ± 0.03	0.16 ± 0.02	<0.04	Ir
Au	0.047 ± 0.005	0.019 ± 0.009	0.124 ± 0.012	0.013 ± 0.006	0.033 ± 0.007	0.012 ± 0.005	0.020 ± 0.006	<0.019	Au
Zn	2930. ± 50.	3590. ± 80.	3890. ± 70.	5510. ± 80.	50. ± 20.	72. ± 15.	<80.	79. ± 12.	Zn



**WATSON 002—THE FIRST CK/TYPE 3 CHONDRITE.** T. Geiger<sup>1</sup>, B. Spettel<sup>2</sup>, R. N. Clayton<sup>3</sup>, T. K. Mayeda<sup>3</sup>, and A. Bischoff<sup>1</sup>. <sup>1</sup>Institut für Planetologie, Wilhelm-Klemm-Strasse 10, 48149 Münster, Germany, <sup>2</sup>Max-Planck-Institut für Chemie, P. O. Box 3060, 55020 Mainz, Germany, <sup>3</sup>Enrico Fermi Institute, University of Chicago, Chicago IL 60637, USA.

The CK chondrites studied so far are all of petrologic types 4–6. In 1991 Watson 002, a petrologic type 3 carbonaceous chondrite, was found in the Nullarbor Region, South Australia, and was classified as “CK3 anomalous” [1]. The supplement “anomalous” was added because it shows some features that do not fit into the mineralogical [2] or bulk chemical [3] characteristics of the CK chondrite group. Here we report on the petrography and mineralogy as well as bulk chemistry and O isotopic composition of Watson 002.

**Petrography and Mineralogy:** The piece we studied has a 3–5-mm-wide margin that shows a less-compacted texture, which seems to be caused by terrestrial weathering. Watson 002 has a chondritic texture characterized by abundant chondrules, inclusions, and fragments embedded in a matrix. Matrix is the most comprehensive textural unit, making up 70 vol% of the meteorite. Chondrules, inclusions, and fragments (grain size > 100 µm) are present in modal portions of about 10 vol% each determined by point counting methods. The mean apparent diameter of 43 detected chondrules is 870 ± 380 µm, ranging from 160–2100 µm. The mineral chemistry of olivines, pyroxenes, and plagioclases is comparable to other CK chondrites. Olivines and pyroxenes in some chondrules and fragments are not equilibrated. Almost pure forsterites (Fa0.3) and enstatites (Fs1.6) occur in the core. Olivines at the edge contain ~20 mol% Fa. Like in other CK chondrites, chondrules are frequently rimmed by magnetite. Matrix olivines have a mean Fa content of 34.4 mol% (range 31–38 mol%), and contain an average of 0.35 wt% NiO. Pyroxenes are less equilibrated than olivines; the composition of the clinopyroxenes vary from 6.7 to 19.9 mol% Fs. Two low-Ca pyroxenes with Fs23.1 and 24.4 were found. Plagioclases occur with An contents from 26.8 to 50.1 mol%.

Unlike the other known CK chondrites, Watson 002 contains abundant CAIs that consist of An-rich plagioclase, olivine, and green pleonast-spinel as the main phases. Similar spinel phases were reported from Maralinga 001 [4] and Karoonda [5]. The pleonasts contain small amounts of Cr and Ti (0.25 wt% Cr<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> respectively). Like in other CK chondrites, the most abundant opaque phase is magnetite that contains about 3.1 wt% Cr<sub>2</sub>O<sub>3</sub> and 1 wt% TiO<sub>2</sub>, but we did not find the exsolution of ilmenite and spinel [6]. Sulfides are rare—only a few micrometer-sized pentlandite grains were found.

**Bulk Chemistry and O Isotopes:** Watson 002 shows an unusual enrichment of Na, K, Ba, and light REE. Different INA analyses of the core and the weathered margin show enrichment of these elements in the margin up to 50× CI, whereas the core shows a “normal” CK pattern. Therefore we conclude that the high abundance of these elements in the weathered margin is due to terrestrial weathering. Besides that, there is a strong enrichment of Ca (4.7× CI) and Ti (~9× CI) in the core, which can be explained in the case of Ca by the high abundance of CAIs compared to other CK chondrites. Titanium is predominantly located in magnetite and spinels.

The O isotopic composition differs from that of other CK chondrites. Previously analyzed CK chondrites plot within the range of the CO chondrites [7], but Watson plots at the uppermost end of the

CV chondrite range and the lowermost end of the CM range. The oxygen isotopic ratios are  $\delta^{18}\text{O} = +5.12$  and  $\delta^{17}\text{O} = -0.55$ . The composition of a single chondrite was found to be  $\delta^{18}\text{O} = +0.56$ ,  $\delta^{17}\text{O} = -3.31$ , which lies within the range of CV chondrules, and is unequilibrated with the bulk meteorite.

**References:** [1] Wlotzka F. (1993) *Meteoritics*, 28, 1. [2] Geiger T. and Bischoff A. (1991) *Meteoritics*, 26, 337. [3] Kallemeyn et al. (1991) *GCA*, 55, 881–892. [4] Keller L. P. et al. (1991) *Meteoritics*, 27, 87–91. [5] MacPherson G. J. and Delaney J. S. (1985) *LPS XVI*, 515–516. [6] Geiger T. and Bischoff A. (1990) *LPS XXI*, 409–410. [7] Clayton R. N. and Mayeda T. K. (1989) *LPS XX*, 169–170.

**PRODUCTION OF KRYPTON AND XENON ISOTOPES BY GALACTIC PROTONS.** E. Gilibert<sup>1</sup>, B. Lavielle<sup>1</sup>, G. N. Simonoff<sup>1</sup>, R. Rösel<sup>2</sup>, U. Herpers<sup>2</sup>, M. Schnatz-Büttgen<sup>3</sup>, M. Lüpke<sup>3</sup>, and R. Michel<sup>3</sup>. <sup>1</sup>C.E.N. Bordeaux-Gradignan, France, <sup>2</sup>Abteilung Nuklearchemie, Universität zu Köln, Germany, <sup>3</sup>Zentraleinrichtung für Strahlenschutz Universität Hannover, Germany.

The production of Kr from target elements Rb (Rb<sub>2</sub>SO<sub>4</sub>), Sr (SrF<sub>2</sub>), Y, and Zr and of Xe in Ba (Ba glass) and La (LaF<sub>3</sub>) is studied in a simulation experiment of the galactic cosmic ray proton bombardment of stony meteoroids in space [1,2]. This investigation is part of the experiment LNS 172, in which a 50-cm-diameter artificial meteoroid (gabbro) was isotropically irradiated at Saturne with 1.6-GeV protons.

Measurements of Kr production vs. depth are now complete in the four investigated target elements. In the <sup>81</sup>Kr–<sup>83</sup>Kr dating method, the production ratio  $P_{81}/P_{83}$  can be evaluated from the cosmogenic spectrum of Kr in the meteorite according to the formula  $P_{81}/P_{83} = 0.95[(^{80}\text{Kr}/^{83}\text{Kr})_c + (^{82}\text{Kr}/^{83}\text{Kr})_c]/2$  [3] where  $(^{80}\text{Kr}/^{83}\text{Kr})_c$  and  $(^{82}\text{Kr}/^{83}\text{Kr})_c$  represent the measured cosmogenic ratios assuming no contribution from (n,γ) nuclear reactions on Br. Applying this formula to this experiment, a good agreement with the measured production ratio is obtained for Zr and Y targets. On the other hand, this formula overestimates the measured production ratio by 6% for Sr and 15% for Rb. Taking a mean composition of ordinary chondrites [4], the production ratio <sup>81</sup>Kr/<sup>83</sup>Kr decreases from the surface to the center by 4%, but the value calculated with the formula still exceeds the measured ratio by 7%. The ratio <sup>78</sup>Kr/<sup>83</sup>Kr also shows a decrease by 10% from the surface to the center. Variation by 20% of the concentration of target elements can change this ratio by 10%, but for the same variation, dependence on the target chemistry is less than 4% for <sup>81</sup>Kr/<sup>83</sup>Kr.

For Xe, depth profiles of production in Ba and La are reported. Production of <sup>126</sup>Xe shows a steep increase from the surface to center by a factor of 1.5 for Ba and of 2 for La. All the production ratios also increase from the surface to the center except <sup>124</sup>Xe/<sup>126</sup>Xe, which is decreasing and <sup>136</sup>Xe/<sup>126</sup>Xe, which is almost constant.

**Acknowledgments:** This work was partially supported by C.N.R.S., by IN2P3, and by INSU (Programme National de Planétologie).

**References:** [1] Michel R. et al (1991) *Meteoritics*, 26, 372a. [2] Gilibert et al. (1992) *Meteoritics*, 27, 223. [3] Marti K. (1967) *Phys. Rev. Lett.*, 18, 264–266. [4] Wasson J. T. and Kallemeyn G. W. (1988) *Phil. Trans. R. Soc.*, A325, 535–544.