

and three others cooled at >1000 K/m.y. They cited these data as supporting the onion-shell model, but they omitted the 50 K/m.y. a value of [2] for H3.8 Dhajala (which shows that some H3 chondrites cooled more slowly than some H4).

Pellas et al. [4] found that the ratio of the density of fission tracks in pyroxene to that in merrillite is lower in H4 than in H6 chondrites, suggesting that the H6 chondrites cooled more slowly. However, one of the “unshocked” H6 chondrites in their set (Kernouve) has been shocked and annealed [5,6]; minor silicate darkening in H6 Guarena [6] suggests a similar history. Because phosphate has a lower impedance to shock compression than pyroxene, shock may be partly responsible for the high pyroxene/merrillite track densities of the H6 chondrites. The correlation obtained by [4] may thus be an artifact.

The less-extensive datasets for metallographic [2] and fission track [1] cooling rates also do not support onion shells for the L and LL bodies.

Göpel et al. [7] recently determined the  $^{207}\text{Pb}/^{206}\text{Pb}$  model ages of phosphates in seven H chondrites and found a negative correlation between age and petrologic type. Although these data seem consistent with an onion-shell structure, there is no concordancy between Pb/Pb systematics and different radiochronometers. Furthermore, the metamorphic temperatures of type 4 OC (~920 K) are probably lower than the U/Pb closure temperature of the phosphates [7], casting doubt on what the Pb/Pb ages of type-4 OC are actually measuring. Göpel et al. also determined the internal U/Pb systematics of H3.4 Sharps and obtained a Pb/Pb age that is younger than that of H6 chondrites, inconsistent with an onion-shell structure for the H asteroid.

A large OC body with an onion-shell structure should exhibit an inverse correlation between petrologic type and  $^{39}\text{Ar}$ - $^{40}\text{Ar}$  age. Pellas and Fieni [8] found no such correlation in H chondrites: 11 of 12 H chondrites in their study have Ar-Ar ages within the same narrow range ( $4.48 \pm 0.04$  b.y.). They concluded that the H body was small, but their data do not indicate it had an onion shell. Pellas and Fieni also found that five LL3–LL5 chondrites have about the same age (4.48–4.51 b.y.), but that three LL6 chondrites are younger (4.38–4.42 b.y.). Although these data are consistent with an LL onion shell, they are in conflict with available Pb/Pb model ages [7] and metallographic cooling rates [2].

The evidence for onion-shell structures in OC parent bodies is weak.

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**ON THE EVOLUTION OF THE LUNAR CORE.** S. K. Runcorn<sup>1,2,3</sup>, <sup>1</sup>Max-Planck-Institut für Chemie, Mainz, Germany, <sup>2</sup>University of Alaska, Fairbanks, Alaska, USA, <sup>3</sup>Physics Department, Imperial College, London, UK.

Strong magnetic, dynamic, and chemical evidence now exists for a lunar Fe core, in which a dipole magnetic field was generated by the dynamo process sometime between 4.0 Ga and 3.2 Ga. The first argument that was presented requiring a core was that the nonhydrostatic second harmonic term in the lunar figure is maintained by solid-state convection and is not a relic of a primeval distortion retained by finite strength. This two-cell convection would have developed only in the presence of a core of radius between 400 and 600 km. However, there is evidence that a one-cell convection predominated in the early history of the Moon. First, the successive polar reorientations between 4.0 Ga and 3.8 Ga discovered from palaeomagnetism would not have been possible if the Moon's gravitational field had then a second harmonic term. Second, evidence for the absence of the latter exists in the palaeoselenoid “frozen into” the maria surfaces. Third, a one-cell convection seems to be the explanation of the thicker farside highland crust, inferred from the offset of the center of figure from the center of gravity.

It is therefore suggested that there was no core prior to about 4.0 Ga and this appears to be the simplest explanation of the paleointensity curve, the magnetic field strength derived from laboratory studies of the Apollo rocks. The paleointensity declined exponentially from a high value of about 1 Gauss

at about 3.9 Ga, or a little later, to 0.02 Gauss at 3.2 Ga—presumably reflecting the decreasing energy driving convection in a then fluid core. However, in the 100–200 m.y. prior to the maximum field, the paleointensity rose rapidly. This would have a simple explanation if the core only started growing about 4.0 Ga.

This suggestion would imply a cold origin of the Moon, with the magma ocean only 200 km deep, the heat source for which was limited to shallow depths as in the proposal of induction by an intense primeval solar wind. Radioactive heating especially by  $\text{U}^{235}$  in the first 500 m.y. would have raised the temperature of the originally cold interior to the KREEP threshold, in which the initially uniformly distributed Fe and FeS would have been convected to form a core.

**ON THE ORIGIN OF THE SUPPOSED MAGNETIZATION OF GASPRA.** S. K. Runcorn<sup>1,2,3</sup>, <sup>1</sup>Max-Planck-Institut für Chemie, Mainz, Germany, <sup>2</sup>University of Alaska, Fairbanks, Alaska, USA, <sup>3</sup>Physics Department, Imperial College, London, U.K.

Kivelson et al. [1] have interpreted a reversal of magnetic field direction in the solar wind as the Galileo spacecraft encountered Gaspra as a shock front produced by the asteroid. The obstacle it presents to the solar wind has to be much greater than its dimensions and this is interpreted as a magnetic field. The inferred intensity of magnetization is in the range observed in meteorites.

While small bodies such as chondrules and perhaps some meteorites may acquire a thermoremanent magnetization from the solar nebula magnetic field as they cool, it is unlikely that the spin axis of larger bodies could have remained fixed relative to the magnetic field for a sufficient time. Thus the question arises whether Gaspra's magnetization was acquired while it was in a parent body with a magnetic field. In a small accreted body heated by  $\text{Al}^{26}$  an Fe core of about 100 km diameter could have formed that produced a magnetic field by dynamo action. The recent discovery of evidence for  $\text{Fe}^{60}$  in the early solar system suggests that an Fe core could have remained molten and vigorously convecting for some million years, generating a mean field along its axis of rotation and therefore in a direction fixed with respect to the proto-Gaspra in its mantle. For it to acquire remanent magnetization it has to cool through the Curie point to low temperature while the field is present, i.e., before the core cools. Asteroids, known to possess thick regoliths, might cool quickly to 10 km depth if these were removed by collisions, and a protoasteroid in this outer shell could then become uniformly magnetized. Further collisions could dislodge the asteroid.

**References:** [1] Kivelson M. G. et al. (1993) *Science*, 261, 331–334.

**AN ION MICROPROBE STUDY OF CAIs FROM CO3 METEORITES.** S. S. Russell<sup>1</sup>, R. C. Greenwood<sup>2</sup>, A. J. Fahey<sup>1</sup>, G. R. Huss<sup>1</sup>, and G. J. Wasserburg<sup>1</sup>, <sup>1</sup>Division of Geological and Planetary Sciences, 170-25, Caltech, Pasadena CA 91125, USA, <sup>2</sup>Natural History Museum, Cromwell Road, London, SW7 5BD, UK.

When attempting to interpret the history of Ca, Al-rich inclusions (CAIs) it is often difficult to distinguish between primary features inherited from the nebula and those produced during secondary processing on the parent body. We have undertaken a systematic study of CAIs from 10 CO chondrites, believed to represent a metamorphic sequence [e.g., 1], with the goal of distinguishing primary and secondary features. ALHA 77307 (3.0), Colony (3.0), Kainsaz (3.1), Felix (3.2), ALH 82101 (3.3), Ormans (3.3), Lancé (3.4), ALHA 77003 (3.5), Warrenton (3.6), and Isna (3.7) were examined by SEM and optical microscopy. We have identified 141 CAIs within these samples, and studied in detail the petrology of 34 inclusions.

The primary phases in the lower petrologic types are spinel, melilite, and hibonite. Perovskite, FeS, ilmenite, anorthite, kirschsteinite, and metallic Fe are present as minor phases. Melilite becomes less abundant in higher petrologic types and was not detected in chondrites of type 3.5 and above, confirming previous reports that this mineral easily breaks down during heating [2]. Iron, an element that would not be expected to condense at high temperatures, has a lower abundance in spinel from low-petrologic-type mete-

TABLE 1.

Meteorite	Incl.	Description	$(^{26}\text{Al}/^{27}\text{Al})_0 \pm 1\sigma$	n	$\chi^2 (1\sigma)$
ALH 77307 (3.0)	SP4	Melilite only, 150 $\mu\text{m}$	$(6.1 \pm 1.3) \times 10^{-5}$	4	0.2
	SP5	Melilite only, 150 $\mu\text{m}$	$(6.5 \pm 1.4) \times 10^{-5*}$	4	0.7
	SP7	Melilite + hibonite, 80 $\mu\text{m}$	$(5.0 \pm 0.3) \times 10^{-5*}$	3	0.7
ALH 82101 (3.3)	SP15	150 $\mu\text{m}$ fassaite + hibonite microspherule	$<5 \times 10^{-6}$	3	
	SP1	1 mm melilite aggregate	$(7.0 \pm 3.5) \times 10^{-5}$	6	4.5
Lance (3.4)	SP2	Melilite + kirschsteinite + FeS, 200 $\mu\text{m}$	$(3.8 \pm 1.0) \times 10^{-5}$	5	3.8
ISNA (3.7)	SP11	200 $\mu\text{m}$ spinel + anorthite	$<4 \times 10^{-6}$	2	
	SP16	90 $\mu\text{m}$ hibonite crystal	$(2.9 \pm 0.5) \times 10^{-5*}$	2	1.1

\* Forced through terrestrial  $^{26}\text{Mg}/^{24}\text{Mg}$  at  $\text{Al}/\text{Mg} = 0$ .

orites than those of higher grade, and  $\text{CaTiO}_3$  is replaced by  $\text{FeTiO}_3$  in meteorites of higher petrologic type [3]. The abundance of CAIs is similar in each meteorite. The size of the inclusions is typically 50 to 250  $\mu\text{m}$ , although one melilite-bearing inclusion (SP1) from ALH 82101, with an aggregated texture, is over 1 mm across. We also located two hibonite-bearing microspherules, in Colony and ALH 82101, that are similar to those found in Murchison and Lancé [4].

Eight inclusions have been analyzed by ion probe. The results are summarized in Table 1. Three melilite-bearing inclusions from ALH 77307 (3.0) all contain radiogenic  $^{26}\text{Mg}$  ( $^{26}\text{Mg}^*$ ) that yield  $(^{26}\text{Al}/^{27}\text{Al})_0 \sim 5 \times 10^{-5}$ . The large melilite inclusion in ALH 82101 (3.3) clearly contains  $^{26}\text{Mg}^*$ , although the  $\text{Al}/\text{Mg}$  system shows evidence of disturbance. Microspherule SP15 contains Mg with normal isotopic composition, like other inclusions of this type [4]. A partially altered melilite inclusion from Lance (3.4) contained  $^{26}\text{Mg}^*$ . An anorthite-rich inclusion from Isna (3.7) contained no  $^{26}\text{Mg}^*$ , but a single hibonite crystal from the same section with an  $\text{Al}/\text{Mg}$  ratio of  $>2000$  contained  $\text{Mg}^*$  corresponding to a  $(^{27}\text{Al}/^{26}\text{Al})_0$  value below the canonical figure. The results obtained to date show that CAIs in CO meteorites, like those from other meteorite classes, contain  $\text{Mg}^*$  and that Mg in some inclusions has been redistributed.

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**References:** [1] Scott and Jones (1990) *GCA*, 54, 2485–2502. [2] Wark (1981) *LPS XXII*, 1145–1147. [3] Greenwood R. C. et al. (1992) *Meteoritics*, 27, 229. [4] Ireland et al. (1991) *GCA*, 55, 367–379.

**ORIGIN OF CAI RIMS BY VAPORIZATION AND METASOMATISM.** A. Ruzicka and W. V. Boynton, University of Arizona, Tucson AZ 85721, USA.

On their margins most Ca,Al-rich inclusions (CAIs) contain thin "rims" comprised of multiple mineral layers. Previous work has shown that the bulk composition of the rims can be explained by a combination of vaporization during flash heating of the CAIs and a metasomatic event that involved an influx into CAIs of Mg and Si [1–3]. The layering structure of rims may have formed by a coupled reaction/diffusion process during metasomatism, similar to that which produced mineralogically zoned olivine coronas in mesosiderites [4]. Here we discuss additional data that better define the interplay between vaporization and metasomatism in forming CAI rims, based on microprobe and SEM studies of CAIs in the Vigarano, Leoville, and Efremovka CV3 chondrites.

Rim layers consist mainly of spinel (sp), forsteritic olivine (ol), Ti, Al-rich pyroxene (Tpx), Al-rich diopside (Al-diop), melilite (mel), anorthite (anor), and lesser amounts of perovskite (pv), Fe-Ni metal, and feldspathoids. The rim sequence is essentially the same on CAIs of all petrographic types (A–C) and in CAIs composed of aggregated objects, although individual layers are often missing or very thin. The idealized sequence is mel-rich CAI interior  $\rightarrow$  sp-rich layer  $\rightarrow$  mel/anor layer  $\rightarrow$  Tpx  $\rightarrow$  Al-diop  $\rightarrow$  ol-rich layer  $\rightarrow$  matrix. Olivine grains in the ol layer are embedded in Al-diop or diop, and appear to have pre-existed layer formation [5]. The sp layer con-

tains an intimate mixture of sp, Tpx, mel, anor, and pv, and sometimes shows an apparent igneous texture consisting of blocky or acicular sp surrounded by Tpx and mel. Unlike other layers, the sp layer sometimes meanders into CAI interiors, suggesting that it may have formed differently than the other layers.

**Metasomatism:** If flash heating alone affected rims, then they should be consistently enriched in refractory elements compared to the CAI interior, but this is not the case. Relative to the mel-rich substrate, bulk rim layers are typically enriched in Ti, Mg, Si, Cr, Fe, Na, and Cl, and depleted in Al and Ca. The enrichment of the refractory element Ti may be ascribed to flash heating, and the enrichment of the volatile elements Na and Cl is certainly caused by alkali-halogen alteration, but the enrichment of non-refractory elements (Mg, Si, Cr, Fe) is best explained by their addition to CAIs from an external medium during metasomatism. The external medium appears to have been rich in ferromagnesian elements, and could have been similar either to the forsteritic olivine in the outermost layer or to chondritic matrix. This ferromagnesian material may have been present as "dust" that coated still-hot CAIs shortly after flash heating.

**Vaporization:** The average concentration ratio (bulk silicate layers)/(bulk spinel-rich layer) increases in the order  $\text{Al} < \text{Ti} < \text{Ca} \sim \text{Mg} < \text{Si}$ , which indicates that the inner spinel-rich layer is enriched in refractory elements compared to the outer silicate layers. This gradient can be explained by the addition of nonrefractory "chondritic" material to rims that had previously undergone volatility-dependent vaporization. The Al and Si content of the sp layer is correlated with the type and composition of CAI (from types A to B to C, Al decreases while Si increases in both the sp layer and underlying inclusions), consistent with the idea that the sp layer was partially derived from the underlying CAI. The sp layer may thus largely be a vaporization residue in which spinel was concentrated because of its stability at high temperatures in a refractory melt.

**References:** [1] Boynton W. V. and Wark D. A. (1987) *LPS XVIII*, 117–118. [2] Wark D. A. and Boynton W. V. (1987) *LPS XVIII*, 1054–1055. [3] Wark D. A. et al. (1988) *LPS XIX*, 1230–1231. [4] Ruzicka A. et al. (1994) *GCA*, in press. [5] Ruzicka A. and Boynton W. V. (1993) *Meteoritics*, 28, 426.

**ION MICROPROBE STUDIES OF A CARBONACEOUS (CM) XENOLITH IN THE EREVAN HOWARDITE.** S. Sahijpal<sup>1</sup>, M. A. Nazarov<sup>2</sup>, and J. N. Goswami<sup>1</sup>, <sup>1</sup>Physical Research Laboratory, Ahmedabad, 380009, India, <sup>2</sup>Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow 117975, Russia.

The presence of carbonaceous (CM) xenoliths in the Erevan howardite has been reported recently by Nazarov et al. [1]. The carbonates present in these clasts occur as rounded aggregates and are fine grained and extremely pure in composition. Although they resemble CAIs in morphology and texture, no relic refractory phases are present in them. These features and the absence of associated secondary phases (iron sulfide, dolomite, etc.) led Nazarov et al. to propose these carbonates to be of nebular origin even though carbonates are generally not considered to be a stable phase under normal solar nebular conditions. A unique fragment of P-rich sulfide was also found in one of the carbonaceous clasts. A highly reduced nebular environment characterized by high S fugacity was proposed as the formation site of this unique fragment, which was later incorporated into the carbonaceous matrix.

We have used the ion microprobe to determine Ca isotopic compositions of several of the carbonate inclusions and S isotopic composition of the P-rich sulfide. Here we present the results of our Ca isotopic studies; results on S isotopic composition will be reported at the meeting. Although the fine-grained carbonates are extremely pure in composition, we have detected small signals of Mg in all the inclusions, and at times we have detected very small signals of Si and Ti during isotopic analysis. These signals presumably come from the material present in the small veins that cut through the carbonate inclusions. Whenever any signal of Ti was detected, we elected to work at very high mass resolution ( $M/\Delta M \sim 10,000$ ) so that the isobaric interference of  $^{48}\text{Ti}$  on  $^{48}\text{Ca}$  is resolved.  $\text{Sr}^{++}$  signal was also monitored at mass 43.5. However, the signal was below detection limit in all the analysis and no correction was applied. Terrestrial carbonate was also analyzed to monitor