

## THE LIGHT ELEMENT GEOCHEMISTRY OF YAMATO-793605

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**Abstract:** Carbon, nitrogen, neon and argon abundances and isotopic compositions have been determined by stepped combustion-mass spectrometry on aliquots of the lherzolitic shergottite Yamato (Y)-793605. The meteorite has the lowest carbon abundance of any martian meteorite so far analysed. Once terrestrial contamination has been removed, Y79 contains only 7.3 ppm carbon with a  $\delta^{13}\text{C} \sim -19\%$ . Carbon can be divided into four separate components, identified on the basis of combustion temperature and isotopic composition: (1) carbonates (possibly calcite; 1.2 ppm with  $\delta^{13}\text{C} \sim -23\%$ ); (2) magmatic carbon (1 ppm;  $\delta^{13}\text{C} \sim -35 \pm 10\%$ ); (3) martian atmospheric species and (4) cosmogenic carbon. The last three components can also be recognised in terms of their calculated nitrogen isotopic compositions. The isotopically-light carbonate in Y79 conforms to the observations made on other shergottites, that these meteorites have not been altered by surficial fluids in contact with the martian atmosphere, but rather contain carbonates produced from primary magmatic fluids. Neon and argon data were acquired simultaneously with nitrogen, but the small temperature increments selected for the analysis (to maximise information from the nitrogen experiment) resulted in low quantities of the noble gases being released, amounts close to that of the system blank. Only  $^{21}\text{Ne}$  yielded an abundance ( $2.2 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ STP}$ ) much higher than the blank, concentrations which, on the basis of their  $^{21}\text{Ne}/^{22}\text{Ne}$  and  $^{20}\text{Ne}/^{22}\text{Ne}$  ratios were found to be a 9:1 mix of cosmogenic neon with terrestrial atmospheric neon (from the blank). The approximate  $^{21}\text{Ne}$  exposure age of Y79 is  $\sim 4$  Myr, slightly higher than values for other lherzolitic shergottites.

### 1. Introduction

The Yamato (Y)-793605 (hereinafter Y79) is a 16 g-sized shergottite, originally recognised by YANAI (1995) as a possible martian meteorite; measurement of its oxygen isotopic composition (MAYEDA *et al.*, 1995; CLAYTON and MAYEDA, 1996) confirmed this classification. Subsequent investigation of the petrology and mineralogy of the meteorite (MIKOUCHI and MIYAMOTO, 1996a, b) placed Y79 in the sub-group of lherzolitic shergottites, along with two other Antarctic meteorites ALHA77005 (A77) and LEW88516 (L88). MIKOUCHI and MIYAMOTO (1996a, b) also identified areas and veins of shock melt in Y79, and thus, like the shergottites EETA79001 (BECKER and PEPIN, 1984) and Zagami (MARTI *et al.*, 1995), Y79 might also contain trapped martian atmospheric species. It is against a backdrop of the light element geochemistry of martian and terrestrial materials that we have placed our study of carbon, nitrogen,

neon and argon in Y79.

In the terrestrial scheme, lherzolites are materials from the upper mantle or lower crust, generally found at the Earth's surface either as ultramafic xenoliths entrained in (crustal) basalts, or in the basal sections of large layered intrusions. Volcanic processes are the mechanism responsible for carrying mantle materials from depth to the surface. The carbon and nitrogen geochemistry of terrestrial lherzolites and basalts has been studied by, *inter alia*, EXLEY *et al.* (1986), MATTEY *et al.* (1989) and PORCELLI *et al.* (1992), in order to constrain models of degassing, volatile recycling and evolution of surface conditions. Carbon occurs in terrestrial basalts as a coating of elemental carbon along grain boundaries, and also as dissolved  $\text{CO}/\text{CO}_2/\text{CO}_3^{2-}$  in silicate minerals (MATTEY *et al.*, 1989); phosphates are also possible sinks for  $\text{CO}_2/\text{CO}_3^{2-}$ . Carbon in mantle xenoliths is also present as diamonds and in fluid inclusions.

The relatively low concentrations of carbon, nitrogen and noble gases in terrestrial igneous rocks necessitates the use of specialised analytical protocols; one such technique is "stepped combustion", whereby carbon, nitrogen and noble gases are removed from the sample by heating through a temperature sequence in the presence of oxygen. Carbon is converted to carbon dioxide gas, which is admitted to a mass spectrometer for isotope analysis; the temperature at which the combustion occurs is diagnostic of the original form of the element (organic, elemental, etc.; WRIGHT and PILLINGER, 1989). Trapped gases (carbon dioxide, nitrogen, noble gases) are liberated when the host assemblage begins to soften or melt; carbonates and nitrates, on the other hand, decrepitate at a recognisable decomposition temperature to give carbon dioxide irrespective of whether or not oxygen is present. Application of the stepped combustion technique enables the effects of contaminant terrestrial organic compounds to be resolved from indigenous carbon-bearing species, and thus discounted, since materials of this nature usually burn at temperatures less than  $\sim 450^\circ\text{C}$ . The same techniques can also be applied to martian basalts.

## 2. Experimental

A small fragment of Y79 weighing  $\sim 102$  mg was provided by Dr. KOJIMA and the NIPR, as part of the consortium study. The material was coarse-grained, and contained abundant black melt glass, presumably shock-produced. To prevent loss of trapped species, the material was not powdered; rather, small chips representing the bulk sample were removed from the main fragment, for analysis. A single chip was analysed for carbon (4.058 mg), and three small chips taken together for nitrogen and noble gas determination (total weight  $\sim 18.972$  mg). An aliquot of black glass was hand-picked from the bulk, for future analysis (technical problems, in the form of a blown filament, precluded this work being completed for the consortium report). Samples were weighed into platinum foil packets (cleaned by combustion in pure oxygen at  $1000^\circ\text{C}$ ) and loaded into one of two gas extraction systems (for dedicated carbon and nitrogen/noble gas analyses). After evacuation, samples were heated, generally in  $50^\circ\text{C}$  or  $100^\circ\text{C}$  increments, from room temperature up to  $1400^\circ\text{C}$  ( $1200^\circ\text{C}$  for carbon). At each step, the temperature was held constant for 30 minutes whilst the sample was exposed to  $\sim 20$  torr of pure oxygen (from the decomposition of copper

oxide). At the end of the extraction period, unused oxygen was removed and the resultant gases purified cryogenically, then quantified. Analysis of isotopic composition was carried out on different mass spectrometers for the different gases: aliquots of CO<sub>2</sub> and N<sub>2</sub> were admitted to magnetic sector (traditional noble gas-type) mass spectrometers operated in static mode for either  $\delta^{13}\text{C}$  or  $\delta^{15}\text{N}$  determination. Relative  $^{20}\text{Ne}/^{21}\text{Ne}/^{22}\text{Ne}$  and  $^{36}\text{Ar}/^{38}\text{Ar}/^{40}\text{Ar}$  abundances were measured on a quadrupole mass spectrometer; the nitrogen and noble gas mass spectrometers were attached to the same extraction line, thus data for nitrogen, neon and argon were acquired on a single aliquot of sample. A second aliquot was required for the carbon determination. Carbon yields were measured on a capacitance manometer to  $\pm 0.2$  ng and  $\delta^{13}\text{C}$  measured to  $\pm 1\%$  on sample sizes down to  $\sim 1.5$  ng. For nitrogen, yields were gained from calibration of the  $m/z$  28 ion beam current and  $\delta^{15}\text{N}$  determined to precisions of  $\pm 5\%$  on samples as small as 0.1 ng of gas. Noble gas abundances were also acquired after calibration of the relevant ion currents on the quadrupole; the minimum sample size measurable was  $\sim 0.2 \times 10^{-9}$  cm<sup>3</sup> g<sup>-1</sup> (STP) for neon and  $\sim 1.5 \times 10^{-9}$  cm<sup>3</sup> g<sup>-1</sup> (STP) for argon, with a precision  $\sim \pm 20\%$  in each case. Typical system blanks are of the order of 0.5 ng carbon, 0.2 ng nitrogen,  $0.2 \times 10^{-12}$  cm<sup>3</sup> g<sup>-1</sup> (STP) for neon and  $0.9 \times 10^{-8}$  cm<sup>3</sup> g<sup>-1</sup> (STP) for argon per temperature increment. Full details of the analytical procedures are given in BOYD *et al.* (1988), WRIGHT *et al.* (1988) and PROSSER *et al.* (1990).

### 3. Results

#### 3.1. Carbon

Combustion of 4.058 mg of Y79 yielded 63 ppm carbon with total  $\delta^{13}\text{C} \sim -26\%$  (Fig. 1 and Table 1). This is the lowest carbon yield measured for a whole-rock martian meteorite: most have total carbon contents of between 100–800 ppm, with  $\delta^{13}\text{C}$  in the range  $-30\%$  to  $-20\%$  (WRIGHT *et al.*, 1986, 1992). Some 88% of the 63 ppm

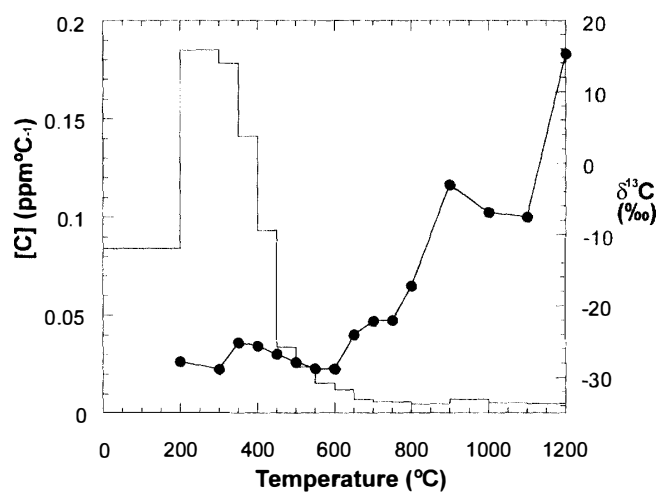


Fig. 1. Carbon in Y-793605. Stepped combustion of 4.058 mg of Y-793605. The yield of carbon released at each step of the experiment, in ppm°C<sup>-1</sup>, is given as a histogram; the corresponding isotopic composition is plotted as dots joined by a line. Errors in  $\delta^{13}\text{C}$  are approximately the size of the symbol.

Table 1. Carbon and nitrogen data from stepped combustion of Y-793605.

Temp. (°C)	[C] (ppm)	$\delta^{13}\text{C}$ (‰)	[N] (ppm)	$\delta^{15}\text{N}$ (‰)
200	16.8	-28	2.69	8
300	18.5	-29	1.11	2
350	8.9	-25		
400	7.1	-26	1.07	26
450	4.7	-27		
500	1.7	-28	0.83	23
550	1.2	-29	0.21	24
600	0.8	-29	0.10	35
650	0.6	-24	0.07	44
700	0.3	-22	0.06	46
750	0.3	-22	0.05	25
800	0.3	-17	0.04	45
850			0.03	43
900	0.4	-3	0.02	68
950			0.03	50
1000	0.7	-7	0.02	143
1050			0.01	105
1100	0.5	-8	0.01	76
1150			0.02	83
1200	0.5	15	0.06	51
1250			0.13	37
1300			0.05	45
1350			0.05	46
1400			0.05	52
Total	63.3	-26	6.71	20

carbon combusts below 450°C, with  $\delta^{13}\text{C} \sim -28\text{‰}$ . As discussed in other papers (e.g. GRADY *et al.*, 1997), much of the carbon present in martian meteorites combusts at low temperatures, and has previously been interpreted as organic material. Notwithstanding the apparent discovery of martian organic compounds in at least two of this group of meteorites (EETA79001, WRIGHT *et al.*, 1989; ALH84001, GRADY *et al.*, 1994; MCKAY *et al.*, 1996), without additional information it is reasonable to assume that these organics are generally of terrestrial contaminant origin. The carbon combusting below 450°C in Y79 has  $\delta^{13}\text{C}$  typical of terrestrial organic contaminants, thus in the remainder of this paper, only the carbon that combusts above 450°C (7.3 ppm;  $\delta^{13}\text{C} \sim -19\text{‰}$ ) is discussed. We have no way, at present, of deciding whether small quantities of indigenous carbon-bearing components with combustion temperatures <450°C are being ignored by this decision.

At intermediate temperatures, between 600°C and 750°C, three consecutive steps give similar  $\delta^{13}\text{C}$  values (between -24‰ and -22‰), defining a plateau. These isotope data are different from the immediately preceding steps ( $\delta^{13}\text{C} \sim -29\text{‰}$ ) and those which follow ( $\delta^{13}\text{C} \sim -17\text{‰}$  and higher). Thus, even though there is not an obvious release of carbon over the 600–750°C interval, it is clear that an isotopically-distinct component is resolved. That a plateau is observed in  $\delta^{13}\text{C}$  argues against substantial mixing with the lower temperature isotopically light carbon, hence it is suggested that

the carbon released between 600–750°C arises from an individual component which amounts to ~1.2 ppm, with  $\delta^{13}\text{C} \sim -23\text{‰}$ . Analysis of ALHA77005 shows a very similar result (WRIGHT *et al.*, 1986), as does LEW88516 (DOUGLAS *et al.*, 1992), although in the latter case, the data are less certain. The temperature is at the high end of the range for carbonates, consistent with identification of the phase as calcite (BOYD *et al.*, 1997), a component which is present in low abundance in many martian meteorites. The isotopically light nature of the carbonate sets it apart from carbonates in the nakhlites, which are  $^{13}\text{C}$ -enriched (WRIGHT *et al.*, 1992), but is similar to carbonates in QUE 94201, Shergotty and Zagami (GRADY *et al.*, 1996, 1997).

Indigenous carbon is released from terrestrial basalts at temperatures above 600°C, when the silicates begin to soften and eventually melt. Carbon occurs as  $\text{CO}_2$  dissolved in the melt, and also as the carbonate anion substituted within the silicate lattice (MATTEY *et al.*, 1989). In martian basalts, there is also the likelihood that  $\text{CO}_2$  trapped from the ambient atmosphere during shock removal of the meteorite from Mars is also present. During subsequent passage of the meteorite from Mars to the Earth, Y79 was exposed to bombardment by cosmic rays. Cosmogenically-produced carbon is firmly bound into the silicate structure, and is not released during a combustion experiment until the silicates break down, which generally occurs at temperatures in excess of ~1100°C. Stepped combustion enables at least partial distinction between primitive martian magmatic carbon, trapped atmospheric species and cosmogenically-derived material. Above 800°C in Y79, some 3.6 ppm carbon combusts, with variable isotopic composition (between  $-17\text{‰}$  and  $+15\text{‰}$ ), indicating that several individual components are present. The carbon released at the highest temperature, by analogy with other martian meteorites, is most probably isotopically light magmatic carbon ( $\delta^{13}\text{C} \sim -30\text{‰}$  to  $-20\text{‰}$ ; WRIGHT *et al.*, 1992) mixed with cosmogenic carbon. An excursion in the  $\delta^{13}\text{C}$  profile observed between 900°C–1000°C (0.4 ppm carbon with  $\delta^{13}\text{C}$  rising to  $-3\text{‰}$ ) could be related to carbon dioxide of martian atmospheric origin trapped within silicates. In order to disentangle magmatic from trapped atmospheric species released at lower temperatures, it is necessary to consider the carbon data in conjunction with nitrogen and noble gas measurements (following sections).

### 3.2. Nitrogen

Y-793605 contains 6.7 ppm nitrogen with  $\delta^{15}\text{N} \sim +20\text{‰}$  (Fig. 2 and Table 1). Again, as discussed for carbon, some 73% of the nitrogen is liberated below 600°C; given its isotopic composition, this component is most probably a mixture of adsorbed terrestrial atmosphere ( $\delta^{15}\text{N} = 0\text{‰}$ ) with terrestrial organic species ( $\delta^{15}\text{N} \sim 0$  to  $+25\text{‰}$ ). The data for nitrogen released at temperatures greater than 600°C are comparable with data from other shergottites (*e.g.*, BECKER and PEPIN, 1984, 1986, 1993; GRADY *et al.*, 1997; Table 2). Above 600°C, the variation in  $\delta^{15}\text{N}$  with temperature indicates that there are again at least three components present. That released at the highest temperatures contains a small contribution from cosmogenic nitrogen; the  $\delta^{15}\text{N}$  of  $+50\text{‰}$  demonstrates mixing with a more isotopically-normal species (presumably magmatic nitrogen).

Between 950°C to 1100°C, 0.03 ppm nitrogen is released, attaining a maximum  $\delta^{15}\text{N} \sim +150\text{‰}$ . Comparison with nitrogen liberated from other shergottites implies

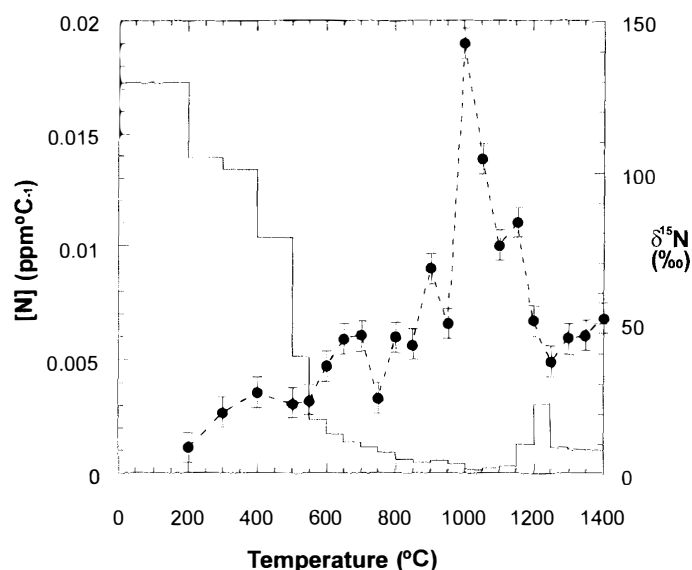


Fig. 2. Nitrogen in Y-793605. Stepped combustion of 18.972 mg of Y-793605. The yield of nitrogen released at each step of the experiment, in  $\text{ppm}^\circ\text{C}^{-1}$ , is given as a histogram; the corresponding isotopic composition is plotted as dots joined by a line. The error bars shown for  $\delta^{15}\text{N}$  are  $\pm 5\%$  ( $1\sigma$ ).

Table 2. Carbon and nitrogen in shergottites ( $T > 600^\circ\text{C}$ ).

Sample	[C] (ppm)	$\delta^{13}\text{C}$ (‰)	Ref.	[N] (ppm)	$\delta^{15}\text{N}$ (‰)	Ref.
Lherzolites:						
Y-793605	3.4	-10	This study	0.34	+46	This study
ALHA77005	8-35	-28 to -18	1			
LEW88516				0.27	+7.3	2
Basalts:						
EETA79001; Lith A	10-24	-18 to -16	1	0.1-0.5	+7	3
EETA79001; Lith B	7-18	-21 to -7	1			
QUE94201	20-38	-27	4	2.0	+28	4
Shergotty	23-82	-27 to -20	1	0.1-0.8	+16 to +46	5
Zagami	30-80	-26 to -23	6	0.6-3.5	-6 to -5	6

References: (1) WRIGHT *et al.* (1986), (2) BECKER and PEPIN (1993), (3) BECKER and PEPIN *et al.* (1984), (4) GRADY *et al.* (1996), (5) BECKER and PEPIN (1986), (6) GRADY *et al.* (1997).

that this component is atmospheric nitrogen trapped from the martian atmosphere ( $\delta^{15}\text{N} \sim +620\%$ ; NIER and MCELROY, 1977), again mixed with isotopically lighter magmatic nitrogen. So, as for carbon, nitrogen in Y79 is a mixture of cosmogenic, magmatic and atmospheric species.

### 3.3. Noble gases

The extraction system employed to release nitrogen from samples also allows separation of neon and argon for isotopic analysis in a quadrupole mass spectrometer. However, the experiment was designed to obtain high resolution nitrogen data, and in

consequence the noble gas data are less well-defined.

**Neon:** As far as neon is concerned, levels of  $^{20}\text{Ne}$  and  $^{22}\text{Ne}$  were close to the system blank for all temperature steps, and it is only for  $^{21}\text{Ne}$  (Fig. 3a) that amounts of gas above system blank were liberated. This does not mean that Y79 contains no neon; it is simply a reflection of the small temperature increments taken for the experiment. If a single stage extraction between  $600^\circ\text{C}$  and  $1400^\circ\text{C}$  had been undertaken, then reasonable, measurable quantities of neon would have been liberated. The total  $^{21}\text{Ne}$  yield of  $2.2 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ STP}$ , and as shown in Fig. 3b, can best be considered as a mixture of cosmogenic neon and terrestrial atmospheric neon (from the system blank). Using a simple lever rule calculation, approximately 10% the total  $^{21}\text{Ne}$  is terrestrial; the remainder is cosmogenic. From the production rate models of EUGSTER and MICHEL (1995) for the average chemical abundances and shielding of basaltic achondrites, and assuming the chemistry of Y79 is closer to that of a diogenite than a eucrite, then a very approximate  $^{21}\text{Ne}$  exposure age can be calculated. The resulting value of  $\sim 4 \text{ Myr}$  is slightly higher than the exposure ages of other lherzolitic shergottites ( $\sim 2.5\text{--}3.5 \text{ Myr}$ ;

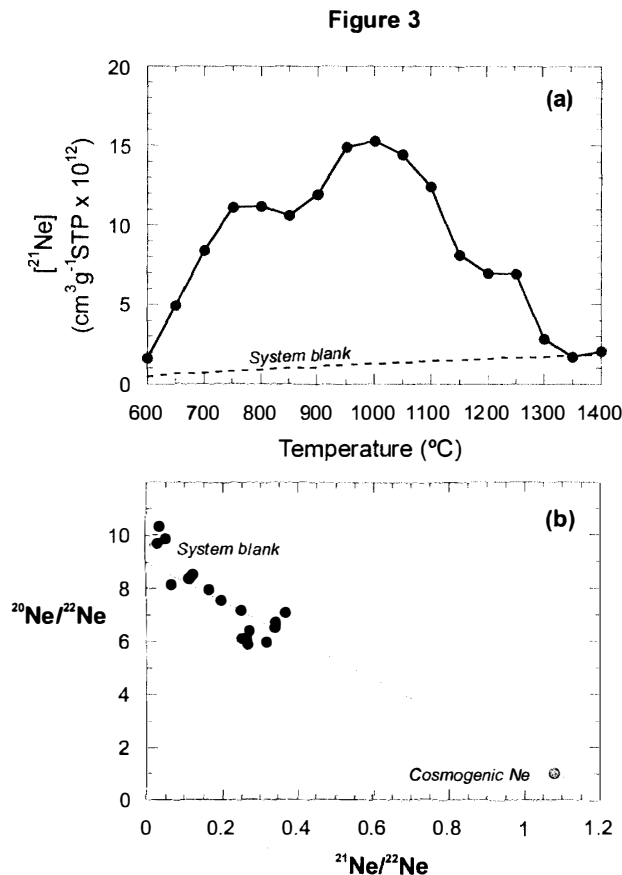


Fig. 3. Neon in Y-793605. (a) Variation in the release of  $^{21}\text{Ne}$  with temperature (dotted line).  $^{21}\text{Ne}$  is the only one of the three neon isotopes which is present in an abundance significantly above that of the system blank (dashed line). (b) The ratios of  $^{20}\text{Ne}/^{22}\text{Ne}$  and  $^{21}\text{Ne}/^{22}\text{Ne}$  indicate that the neon data can best be interpreted as a mixture of system blank with cosmogenic  $^{21}\text{Ne}$ .

EUGSTER *et al.*, 1996).

**Argon:** Unfortunately, in the case of argon, all three of the measurable isotopes had abundances close to the system blank: even the cosmogenically-produced isotope,  $^{38}\text{Ar}$ , was overwritten, a result of the lower production rate of  $^{38}\text{Ar}$  compared to  $^{21}\text{Ne}$ . Notwithstanding the blank problem, since the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of the martian atmosphere ( $\sim 2500\text{--}3500$ ) is very different from that of the terrestrial atmosphere ( $^{40}\text{Ar}/^{36}\text{Ar} \sim 296$ ), the presence of even small amounts of trapped martian atmospheric argon would be manifest on a plot of  $^{40}\text{Ar}/^{36}\text{Ar}$  against temperature. As can be seen in Fig. 4, as a first approximation, there seems to be very little of this species present in the rock, but even so, there is an apparent variation in  $^{40}\text{Ar}/^{36}\text{Ar}$  with temperature. Figure 5 shows that examining the coupled behaviour of argon and nitrogen reveals coincidental maxima in  $\delta^{15}\text{N}$  and  $^{40}\text{Ar}/^{36}\text{Ar}$  at  $1000^\circ\text{C}$  to  $1100^\circ\text{C}$ , implying that the variation in  $^{40}\text{Ar}/^{36}\text{Ar}$  is real, and a result of minor quantities of trapped martian atmospheric species.

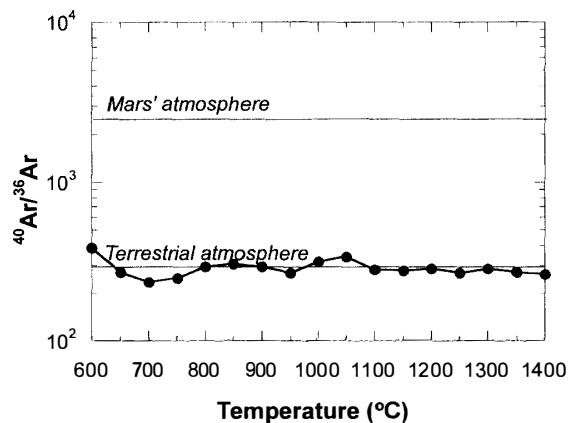


Fig. 4. Variation in  $^{40}\text{Ar}/^{36}\text{Ar}$  with temperature in Y-793605, showing that most of the argon can be ascribed to system blank, with only a very minor contribution from trapped martian atmospheric species.

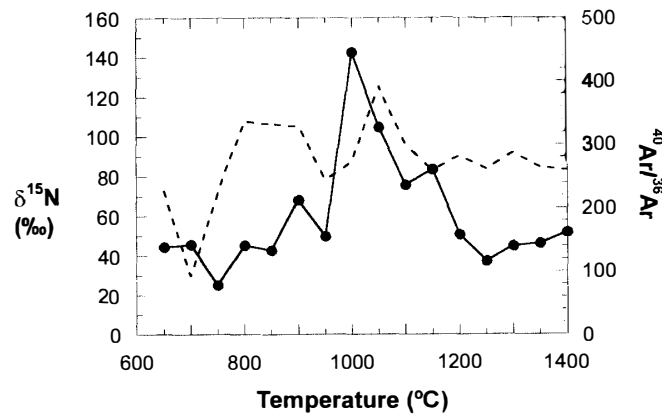


Fig. 5. The coupled variations of nitrogen and argon isotopic compositions with temperature. The coincidence of the maxima in  $\delta^{15}\text{N}$  and  $^{40}\text{Ar}/^{36}\text{Ar}$  imply that there is a minor component of martian atmosphere trapped within the meteorite, which is released between  $1000^\circ\text{C}$  and  $1100^\circ\text{C}$ .



#### 4. Discussion

Although Y-793605 is described as a lherzolite, it turns out to be difficult to interpret its carbon chemistry in the same framework as that of carbon in terrestrial lherzolites. The main reason for this is that carbon in terrestrial lherzolites is not always a true record of primordial terrestrial mantle carbon, but may have been “contaminated” by sedimentary carbon during subduction. This mechanism (absent on Mars) has resulted in a range of isotopic compositions for carbon (mainly as CO<sub>2</sub> in fluid inclusions) in mantle diopsides, from  $-19\%$  to  $-3\%$  (PORCELLI *et al.*, 1992).

The light element geochemistry of Y79 can be compared with that of other martian meteorites, and most specifically with shergottites. The minor carbon-bearing component liberated from Y79 between 600°C and 750°C, identified from the plateau in  $\delta^{13}\text{C}$  at  $\sim -23\%$  has no equivalent release in nitrogen, implying that the material might be either a carbonate or, by analogy with other shergottites (GRADY *et al.*, 1997), carbon substituted in the phosphate anion. Given that MIKOUCHI and MIYAMOTO (1996a, b) specifically highlighted the absence of phosphate grains in the thin sections of Y79 that they studied, it seems likely that if phosphates are present, they are a minor component in this meteorite. Thus the carbon liberated from 600°C–750°C is likely to be from breakdown of a carbonate, rather than from structural substitution in phosphate minerals. The decomposition temperature of the carbonate is characteristic of calcite, rather than Fe- or Mg-rich carbonates (BOYD *et al.*, 1997). The identification of isotopically-light calcite in Y79 (and also in ALHA77005; DOUGLAS *et al.*, 1992) parallels the description of an equivalent component in the basaltic shergottites Zagami and Shergotty (GRADY *et al.*, 1997) and QUE94201 (GRADY *et al.*, 1996). Thus it now seems apparent that shergottites, like nakhlites and ALH84001, contain carbonates. However, the carbonates in nakhlites and ALH84001 are <sup>13</sup>C-enriched (WRIGHT *et al.*, 1992; ROMANEK *et al.*, 1994), and are thought to be formed in near-surface processes from fluids in which martian atmospheric CO<sub>2</sub> is dissolved. In contrast, the carbonates in shergottites (and in Chassigny, WRIGHT *et al.*, 1992) have  $\delta^{13}\text{C}$  values more akin to that proposed for martian magmatic carbon, and thus presumably formed by the action of magmatic fluids at depth within the martian lithosphere, rather than from near-surface reactions. In order to constrain absolutely the origin of the putative carbonate in shergottites, a key measurement is that of the oxygen isotope composition of the carbonates. Unfortunately, at abundance levels of  $\sim 1$  ppm carbon, such a measurement is extremely challenging, and would require sample sizes of 5–10 g of meteorite (Y79 weighed 16 g in total).

Following from the cosmogenic neon results, limits can be placed on the amounts of carbon and nitrogen produced by spallogenic reactions in Y79. Assuming an approximate exposure age of 4 Myr, and a production rate ( $4\pi$  exposure geometry) of  $7.2 \times 10^{-6}$  ppmMyr<sup>-1</sup> for <sup>15</sup>N (BECKER *et al.*, 1976), then  $\sim 0.03$  ppb <sup>15</sup>N is from a spallogenic source. Even though this is a very small quantity of nitrogen, it is sufficient to alter the T>1100°C nitrogen composition by almost 30%, decreasing the measured  $\delta^{15}\text{N}$  from +50% to +23%. A similar calculation for carbon decreases the measured  $\delta^{13}\text{C}$  at 1200°C from +15% to +10%.

Having made this spallogenic correction, to all intents and purposes the remainder of the carbon and nitrogen liberated above 800°C can be considered a mixture of trapped martian atmosphere and “indigenous” magmatic material. For nitrogen, end-member  $\delta^{15}\text{N}$  values of +620‰ for the atmospheric component and 0‰ for magmatic nitrogen are appropriate (BECKER and PEPIN, 1984). Using these values, it is apparent that ~6% of the nitrogen liberated above 800°C is from trapped atmospheric species (*i.e.*, ~28.5 ppb). End-member compositions are less well-established for carbon. Carbon dioxide in the martian atmosphere is inferred to be  $^{13}\text{C}$ -enriched, with the highest value measured at  $\delta^{13}\text{C} \sim +27\text{‰}$  (HARTMETZ *et al.*, 1992). The isotopic composition of magmatic carbon is poorly-constrained ( $\delta^{13}\text{C}$  between  $-30\text{‰}$  and  $-20\text{‰}$ ; WRIGHT *et al.*, 1992). Given that Y79 has a short exposure age, does not contain  $^{13}\text{C}$ -enriched carbonates and apparently hosts ~6% trapped atmospheric species, it should be possible to obtain a more precise value for the  $\delta^{13}\text{C}$  of martian magmatic carbon. This is indeed the case: assuming an atomic C/N ratio for the martian atmosphere of ~16, and relative trapping efficiencies for  $\text{CO}_2$  and  $\text{N}_2$  into basalt of ~2.5:1 (WIENS and PEPIN, 1988), then ~1.1 ppm carbon released above 800°C is from trapped atmospheric species. As detailed above, once the cosmogenic component is subtracted from the carbon inventory, the total carbon above 800°C (2.1 ppm) has a calculated  $\delta^{13}\text{C} \sim -2.4\text{‰}$ . Assuming an end-member composition of +27‰ for the atmosphere (HARTMETZ *et al.*, 1992), then the isotopic composition of the magmatic material is calculated at  $-35\text{‰}$ , slightly lower than the range of values usually quoted (*i.e.*,  $\delta^{13}\text{C}$  between  $-30\text{‰}$  and  $-20\text{‰}$ ; WRIGHT *et al.*, 1992). It seems that the low background level of contaminant carbon, coupled with the short exposure age, both factors precluding swamping of indigenous carbon with additional components, enables deconvolution of the magmatic component in Y79. However, given the uncertainties associated with the procedure, it is appropriate to ascribe relatively large error bars (say,  $\pm 10\text{‰}$ ) to the value calculated. With a  $\delta^{13}\text{C}$  of  $-35 \pm 10\text{‰}$ , the magmatic component in Y79 is comparable with other martian meteorites.

The carbon chemistry of Y79 is very similar to that of other shergottites (WRIGHT *et al.*, 1986; GRADY *et al.*, 1996, 1997), although Y79 has a lower overall carbon abundance and heavier isotopic composition (Table 2), resulting from the influence of martian atmospheric and spallogenic components (the latter despite the short exposure age). Fewer data are available for nitrogen in shergottites, but comparison with the results that have been published (*e.g.*, BECKER and PEPIN, 1984, 1986, 1993; GRADY *et al.*, 1997) show that, as for carbon, Y79 has such a low nitrogen abundance that its overall  $\delta^{15}\text{N}$  is influenced by atmospheric and spallogenic components. In terms of its carbon and nitrogen geochemistry, Y79 is a fairly typical shergottite, unaltered by surficial fluids but retaining a clear magmatic signature in the form of  $^{13}\text{C}$ -depleted carbonates and high temperature carbon dissolved in silicates.

## 5. Conclusions

Y79 contains the lowest amount of carbon measured in any whole-rock martian meteorite, but even so, four separate carbon-bearing components can be identified on the basis of isotopic composition: calcite (1.2 ppm,  $\delta^{13}\text{C} \sim -23\text{‰}$ ); magmatic carbon

(1.1 ppm,  $\delta^{13}\text{C} \sim -35 \pm 10\text{‰}$ ); trapped martian atmosphere and cosmogenic species. The last three of these components can also be seen in the nitrogen isotope profile. Concentrations of  $^{20}\text{Ne}$  and  $^{22}\text{Ne}$  close to the system blank were produced during the narrow temperature increments taken for the analysis, but  $^{21}\text{Ne}$  was present in measurable quantities ( $2.2 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ STP}$ ) as an approximate 9:1 mixture of cosmogenic neon and atmospheric neon (from the system blank). Assuming a  $\text{P}_{21}$  somewhere between values for eucrites and diogenites, and a chemical composition similar to ALHA77005 and LEW88516, then an approximate calculation of the  $^{21}\text{Ne}$  exposure age gives a value of  $\sim 4$  Myr, slightly higher than the results for other lherzolitic shergottites.

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