GEOCHEMISTRY OF AND ALTERATION PHASES IN MARTIAN LHERZOLITE Y-793605

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Abstract: We have done preliminary SEM characterization of alteration phases on an exterior and an interior chip of martian lherzolite Yamato-793605, and have performed instrumental and radiochemical neutron activation analyses of a glass-poor and a glass-rich interior sample of the rock for a suite of 31 major and trace elements. To date, we have identified silica (containing minor amounts of S, K, Fe, Al), K-Fe-sulfate (probably jarosite) and Fe-phosphate as alteration phases in Y-793605. Of these, the silica and K-Fe-sulfate are likely terrestrial weathering products. Other evidence of alteration consists of what appear to be partly decomposed Ca-phosphate grains, which were probably originally igneous grains. No carbonates or Ca-sulfates have been identified as yet, and none of the alteration phases we have identified are unambiguously of martian origin.

Compositionally, Y-793605 is very similar to the other two martian lherzolites ALHA77005 and LEW 88516. Our sample of Y-793605 is lower in the incompatible lithophile trace elements, such as the REE, than the average of either ALHA77005 or LEW 88516, but is within the ranges of individual analyses for ALHA77005. Y-793605 is a partial cumulate like the other lherzolites, but our sample contained less of a trapped melt component.

1. Introduction

Martian meteorites provide planetary scientists with a glimpse of the geologic evolution of a planet that has fascinated humans for centuries. These rocks, now 12 in number, are igneous rocks formed during different times in the geologic history of Mars (*e.g.* MCSWEEN, 1994). Each of them can potentially yield key new information for our growing understanding of the evolution of Mars through time, and hence, each new discovery of a martian meteorite generates intense interest in the meteoritical community.

Yamato-793605 was the eleventh martian meteorite so identified (MAYEDA *et al.*, 1995; YANAI, 1995). Early descriptions of this stone suggested that it was petrologically similar to two other martian meteorites, the plagioclase lherzolites ALHA77005 and LEW 88516 (MIKOUCHI and MIYAMOTO, 1996; YANAI, 1995). Unlike these other two lherzolites, Y-793605 contains a breccia zone (YANAI, 1995) that suggests it might contain some petrologically distinct materials.

In order to increase our knowledge of martian igneous evolution, and to test the possible compositional heterogeneity implied by the breccia material, we undertook geochemical studies of both the normal, igneous lithology of Y-793605 and a sample enriched in the glassy breccia material. We have also begun scanning electron microscope (SEM) studies of interior and exterior chips of the meteorite to identify the alteration products and secondary minerals present, and to attempt to determine which, if any, of these were formed on Mars and which were formed on Earth. Here we report our completed geochemical analyses and our preliminary SEM results.

2. Sample Description and Analytical Methods

We originally submitted an independent sample request to NIPR for the geochemical and chronologic study of Y-793605. On the basis of our request, we were invited to join a consortium study being organized by H. KOJIMA, P. WARREN, M. MIYAMOTO and K. YANAI (KOJIMA *et al.*, 1997). Future work by our group on these samples will include chronologic and noble gas studies by D. BOGARD, L. NYQUIST and their colleagues.

2.1. Samples

The samples we received were several chips massing 724 mg of interior material (,10 and ,71) including both the typical lherzolitic lithology and glass-rich chips, and a small exterior chip (,75) containing abundant, brownish alteration material (see KOJIMA *et al.*, 1997). The lherzolite is a coarse-grained rock, with some orthopyroxene grains up to at least 4 mm in size. Many of the olivine and pyroxene grains are equant and ~1–2 mm in size. Grain boundaries in the sample were indistinct, and the texture could not be identified on the small chips. The interior lherzolite lithology was fairly fresh, although a small amount of yellowish-brown to reddish-brown alteration material was present. One surface contained numerous chalky white crystals that appeared to be possible alteration material. These crystals were distinct from the maskelynite grains present in the rock. The glass-rich material is black, massive (not veins) and vesicular, and contains some mineral fragments. The glass was very fresh; only a few small areas containing reddish alteration material were observed. In hand sample, it appeared to be equivalent to the breccia material shown in thin section (YANAI, 1995). The surfaces of the exterior sample were stained with yellowish-brown alteration material. One surface was polished, probably by the antarctic winds, and so likely represents the exterior surface of the stone.

The exterior sample was set aside for SEM work. The interior samples (,10 and ,71) were carefully chiseled to yield two splits, glass-poor lherzolite (666 mg) and a glass-rich sample (58 mg). One small glass-rich chip of about 26 mg was put aside for noble gas studies by D. BOGARD. The remainder of the glass-rich material (32 mg) was ground up for chemical analyses. The large glass-poor sample (,10) was carefully chiseled to yield a small chip ~20 mg in mass containing some of the alteration material, and this was put aside for SEM study. The remainder (~646 mg –,10 and ,71) was coarsely crushed and homogenized, and a split of ~78 mg was taken for chemical analyses. Most of the remainder was given to D. BOGARD and L. NYQUIST

for chronologic investigations. Because the two interior samples were first combined before separating them into glass-poor and glass-rich samples for chemical analyses, they will be referred to by the joint split numbers ",10-71" here.

2.2. SEM analyses

The scanning electron microscope (SEM) methods used are the same as those used in similar studies of other martian meteorites (GOODING et al., 1988, 1991; WENTWORTH and GOODING, 1993, 1994, 1995). Two, millimeter-sized chips of Y-793605, including samples from both interior (,10) and exterior (,75) portions of the meteorite, were lightly dusted with air and then carbon-coated for electron beam analysis. The studies were performed with a JEOL 35CF SEM equipped with a PGT System IV energy dispersive spectrometry (EDS) system capable of analyzing light elements with atomic number down to carbon.

2.3. Geochemical analyses

The glass-rich and glass-poor splits for chemical analyses were encapsulated in pure SiO_2 glass tubes and irradiated at the University of Missouri Research Reactor (UMRR) for 12 hours at a thermal neutron flux of 5.5×10^{13} n cm^{-2} s^{-1}. The samples were counted in the instrumental neutron activation analysis (INAA) laboratory at Johnson Space Center (JSC) four times over a period of 3 months to yield data for nuclides of differing half lives. Details of the JSC INAA procedures are given in MITTLEFEHLDT and LINDSTROM (1993). After INAA was completed, the samples were transferred to Purdue University for radiochemical neutron activation analysis (RNAA). The samples were removed from the SiO_2 glass tubes, re-encapsulated, and re-irradiated along with appropriate monitors at UMRR for 288 hours at a flux of 8.0×10^{13} n cm^{-2} s^{-1}. After receipt of the samples and monitors from UMRR, they were processed chemically and counted using procedures described by WANG and LIPSCHUTZ (1990). Chemical yields for samples exceeded 50% for all elements except Ag and Au; their yields were 20–40%. Chemical yields for all monitors exceeded 50% in all cases. The neutron fluence received during the second irradiation was sufficiently greater than the INAA irradiation that corrections for prior activity could generally be ignored. Minor corrections (<3%) were made as necessary, however.

3. Results

3.1. SEM analyses

Some alteration is evident on both exterior and interior chips of Y-793605. Areas of the exterior (,75) surface seem to be coated with a thin layer of silica, which contains minor, variable amounts of S, K, Fe, Al, and other elements. Such silica-rich material has previously been documented on exterior surfaces of martian and non-martian antarctic meteorites (e.g., WENTWORTH and GOODING, 1996). Secondary aluminosilicates (clays) may also be present on the exterior sample. The only other secondary mineral found on the surface thus far is K-Fe-sulfate (probably jarosite), which occurs as cavity-filling material. Like the silica, K-Fe-sulfate is a common product of terrestrial weathering of antarctic meteorites.
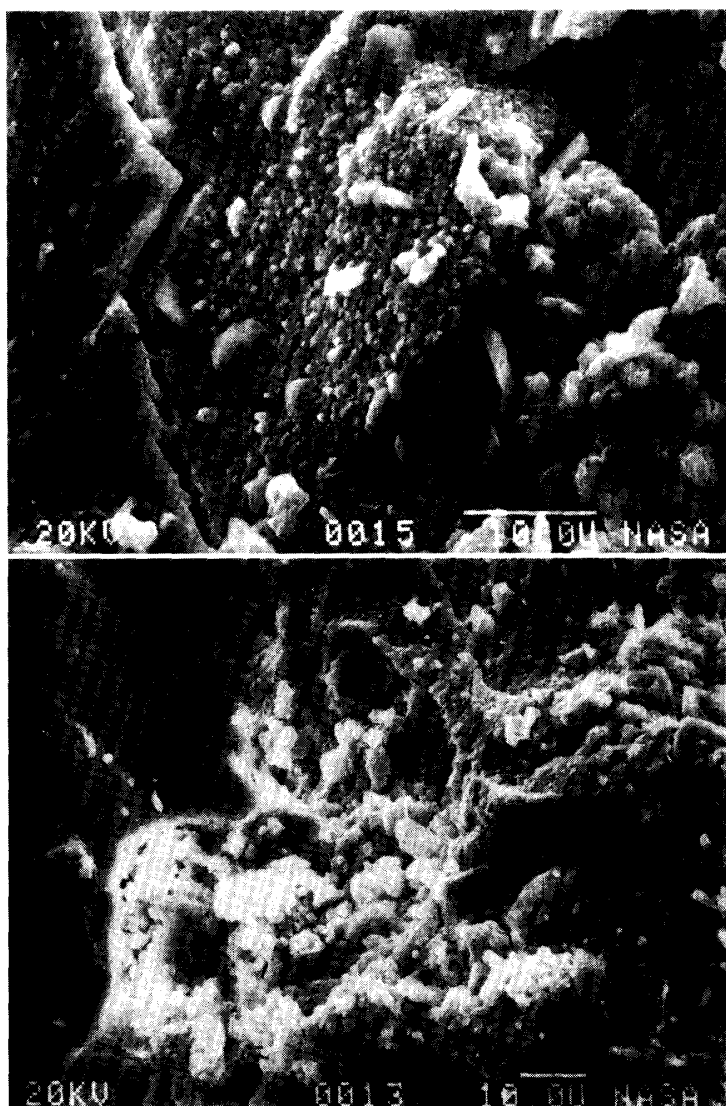
Fig. 1. SEM images of alteration phases in interior sample Y-793605,10.
A. Fe-K-sulfate (jarosite?) grains on a natural fracture surface of the interior sample. Arrows indicate relatively large euhedral crystals.

B. Fine-grained Fe-phosphate (bright material) filling a cavity in the interior sample.

The interior sample (,10) also contains minor K-Fe-sulfate, which occurs as small, blady crystals on natural fracture surfaces (Fig. 1A). The most common alteration . product in ,10 is Fe-phosphate, which occurs both as massive, fine-grained vein and cavity fillings (Fig. 1B) and as thin, scaly layers on fresh silicate substrates (Fig. 1C). Other evidence of alteration in Y-793605 consists of what appear to be partly decomposed Ca-phosphate grains (Fig. 1D), which were probably originally igneous grains. Carbonates and Ca-sulfates have not yet been identified in Y-793605.

3.2. Geochemical analyses

The results of the INAA on the two samples of Y-793605 are presented in Table 1, along with comparative data obtained in our laboratory and from the literature on ALHA77005 and LEW 88516. ALHA77005 has been divided into light and dark lithologies based on the petrology of the samples (LUNDBERG et al., 1990). As can be seen in Table 1, the glass-poor sample is generally poor in the most incompatible

Fig. 1 (Continued).
C. Scaly Fe-phosphate coating silicate on a natural fracture surface of the interior sample. The substrate between the scales has the composition of olivine.
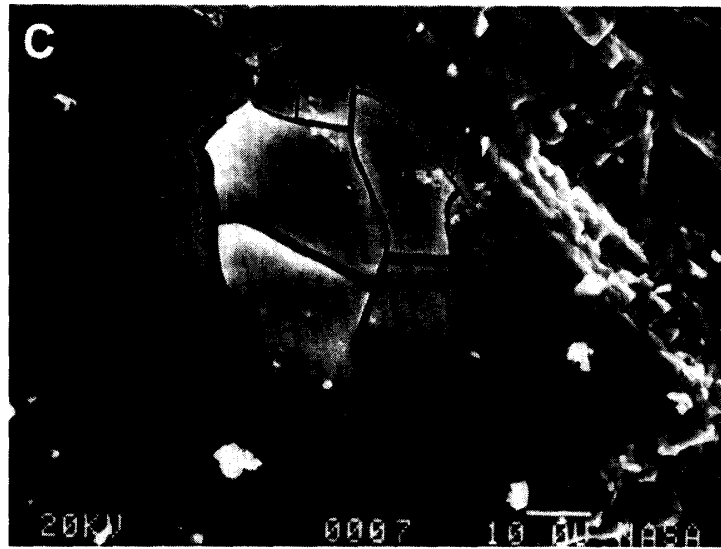
D. Original igneous Ca-phosphate showing a highly pitted surface, suggestive of decomposition.
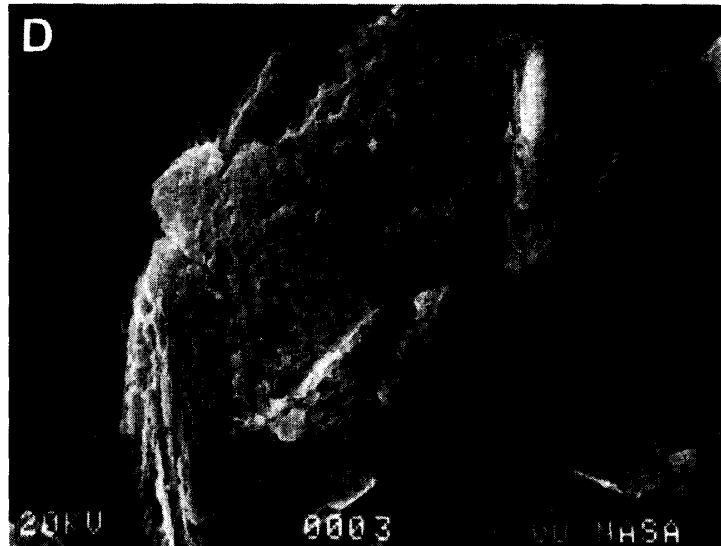
lithophile trace elements, such as the rare earth elements (REE). In this, it is more similar to ALHA77005 light lithology than to dark lithology. The glass-rich sample is enriched in the incompatible lithophile elements compared to the glass-poor sample (Table 1). The only exception to this is Ca, which is slightly depleted in the glass-rich sample. The glass-rich sample is depleted in the compatible lithophile elements Sc and Cr compared to the glass-poor sample, but enriched in FeO, Co and Ni (Table 1). Figure 2 is a REE plot for Y-793605 comparing it to the other martian lherzolites.

The concentrations of 15 trace elements determined by RNAA on the two Y-793605 samples are presented in Table 2. We also list for comparison the geometric mean values for the other two martian lherzolites, and ranges and geometric mean values with associated standard deviations for all 11 other martian meteorites. There are two elements we determined by both INAA and RNAA, Co and Zn. The Co data by RNAA are systematically lower than the INAA data, a feature we have observed during previous collaborations between JSC and Purdue (*e.g.*, TREIMAN *et al.*, 1994). We

Table 1.   INAA data on Yamato 793605,10-71, and comparison with martian lherzolites ALHA77005 and LEW 88516.

		Y-793605[*]			ALHA77005			LEW 88516
		glass-poor	glass-rich	bulk	light	dark	bulk	bulk
Na_2O	wt%	0.257	0.475	0.274	0.207	0.541	0.425	0.458
CaO	wt%	2.7	2.2	2.7	2.7	3.6	3.2	4.1
Sc	µg/g	21.0	16.7	20.7	20.1	22.7	20.4	25.8
Cr_2O_3	wt%	1.26	0.688	1.21	1.28	1.02	1.05	0.92
FeO	wt%	18.8	25.0	19.3	17.5	20.3	19.9	19.3
Co	µg/g	67.3	88.8	69.0	65.0	74.9	72.2	63.1
Ni	µg/g	320	390	330	320	353	320	250
Zn	µg/g	63	68	63	74	90	71	58
La	µg/g	0.173	0.520	0.201	0.156	0.427	0.325	0.316
Ce	µg/g		1.6					
Sm	µg/g	0.264	0.690	0.298	0.216	0.565	0.451	0.434
Eu	µg/g	0.119	0.287	0.132	0.094	0.465	0.241	0.221
Tb	µg/g	0.10	0.24	0.11	0.09	0.19	0.16	0.17
Yb	µg/g	0.36	0.84	0.40	0.33	0.68	0.53	0.55
Lu	µg/g	0.060	0.127	0.065	0.047	0.097	0.076	0.083
Hf	µg/g	0.34	0.86	0.38	0.25	0.67	0.51	0.52
Ta	ng/g		40			40	30	30
Ir	ng/g	4	4	4	7	5	6	2

[*]The masses of the samples analyzed were 77.69 mg for the glass-poor sample and 32.18 mg for the glass-rich sample. The glass-poor sample was a split of ~646 mg of coarsely crushed and homogenized material, while the glass-rich sample represents the entire mass that was crushed for chemical analyses. Uncertainties in the data are as follows: ≤3% –Na_2O, Sc, Cr_2O_3, FeO, Co, Sm, Eu; ~6% –La, Ni, Yb; ~7%–Lu; 6~9%–Tb, Hf; ~10%–CaO, Zn; 14%–Ce; ~35%–Ir.

do not understand the cause of this discrepancy, but because the INAA data are more consistent with the larger body of martian meteorite data, we prefer them. The INAA Zn data are systematically higher than the RNAA data, although the analyses on the glass-rich sample are within analytical uncertainty. The RNAA Zn data are more consistent with the results of WARREN and KALLEMEYN (1997) on Y-793605, and we prefer them.

In Fig. 3 we plot CI-normalized data for the Y-793605 samples, the means for the other two martian lherzolites, and the means and associated standard deviations for all 11 other martian meteorites. As can be seen, only the refractory lithophile element U is at or above cosmic levels in martian meteorites. Moderately volatile to volatile lithophile elements, Ga, Rb, Cs and Zn, lie between 0.2–0.7 times CI abundances in martian meteorites. Indium is also in this range. Siderophile and chalcophile elements are depleted by factors of 0.1 to 0.001 times CI abundances in martian meteorites.

A separate sample of Y-793605 was studied by WARREN and KALLEMEYN (1997) by INAA and RNAA. For the elements determined in common, Fig. 4 compares the UCLA data to our calculated bulk composition (glass-poor plus glass-rich). The two samples contained similar contents of the compatible transition elements Cr, Fe, Co, Ni and Zn, although the UCLA sample was depleted in Cr and Ni. The UCLA sam-
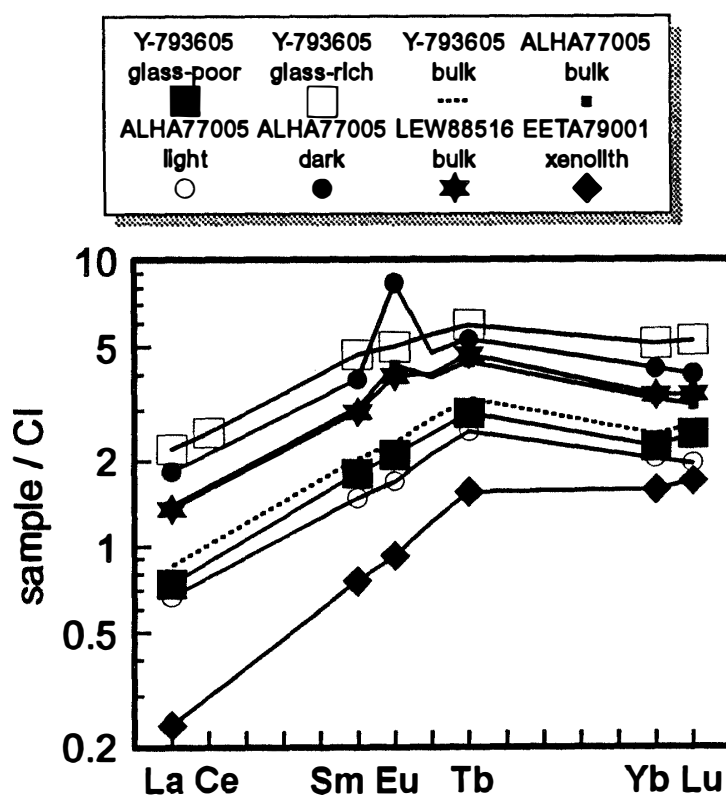
Fig. 2. Rare earth element (REE) diagram for Y-793605, the other martian lherzolites
and an average of three xenoliths from EETA79001 lithology A.

Table 2. RNAA data on Yamato-793605,10-71, and comparison with the mean of martian lherzolites
ALHA77005 and LEW 88516, and ranges, means and associated standard deviations of all other
martian meteorites.

		Y-793605			lherzolite[*]	martian meteorites[**]		
		glass-poor	glass-rich	bulk	mean	rang	mean	std
U	ng/g	7.51	22.9	8.74	17	9.8 − 150	36	+92 / − 14
Au	ng/g	0.16	0.72	0.20	0.39	0.02 − 2.8	0.61	+2.8 / − 0.13
Co	μg/g	32	62	34	63	14 − 73	36	+58 / − 22
Sb	ng/g	0.80	1.1	0.82	0.96	0.68 − 13	3.8	+12 / − 1.2
Ga	μg/g	5.47	7.59	5.64	6.07	0.84 − 20	5.57	+15.8 / − 1.96
Rb	μg/g	0.47	0.54	0.48	0.34	0.19 − 6.7	1.26	+4.2 / − 0.37
Ag	ng/g	2.26	4.75	2.46	5.1	0.24 − 39	7.3	+31 / − 1.7
Se	ng/g	133	306	147	200	25.1 − 473	160	+430 / − 59.2
Cs	ng/g	28.4	39.6	29.3	41	22 − 1100	130	+450 / − 35
Te	ng/g	1.6 ± 0.5	9.5 ± 1.9	2.2	0.45	0.45 − 29	4.5	+17 / − 1.2
Zn	μg/g	46.3	59.8	47.4	50	49 − 110	69	+89 / − 53
Cd	ng/g	8.3	9.6	8.4	8.6	6.0 − 110	36	+97 / − 13
Bi	ng/g	0.47 ± 0.16	0.55 ± 0.28	0.48	2.4	0.66 − 5.1	1.6	+3.5 / − 0.8
Tl	ng/g	3.79	4.27	3.83	2.8	0.10 − 21	3	+12 / − 0.7
In	ng/g	11.4	20.7	12.1	18	11 − 77	26	+45 / − 15

[*]Means are geometric means of all analyses of martian lherzolites ALHA77005 and LEW 88516. For Te
and Bi only single determinations are available.

[**]Means are geometric means of all martian meteorites, excluding Y-793605, and std represents 1σ limits.
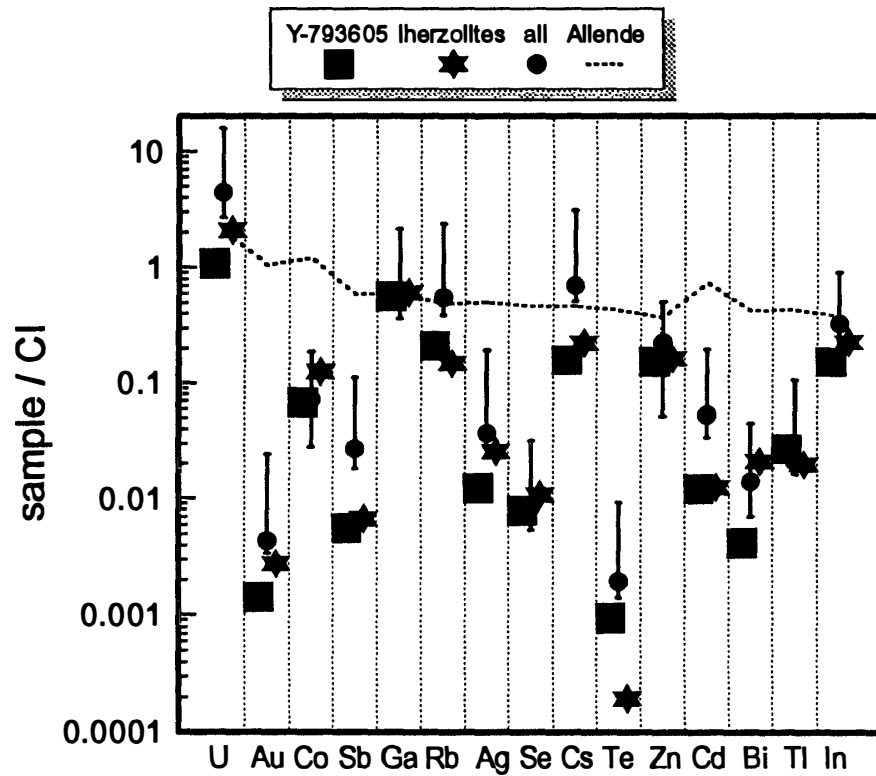
Fig. 3. CI chondrite-normalized volatile/mobile elements in Y-793605 plotted in order of increasing nebular volatility. The geometric mean of the other two martian lherzolites, the geometric mean and standard deviation of all other martian meteorites, and an average of our (LIPSCHUTZ and colleagues) analyses of the CV chondrite Allende are shown for comparison. The Purdue Co data are used in this diagram, which may be systematically low.
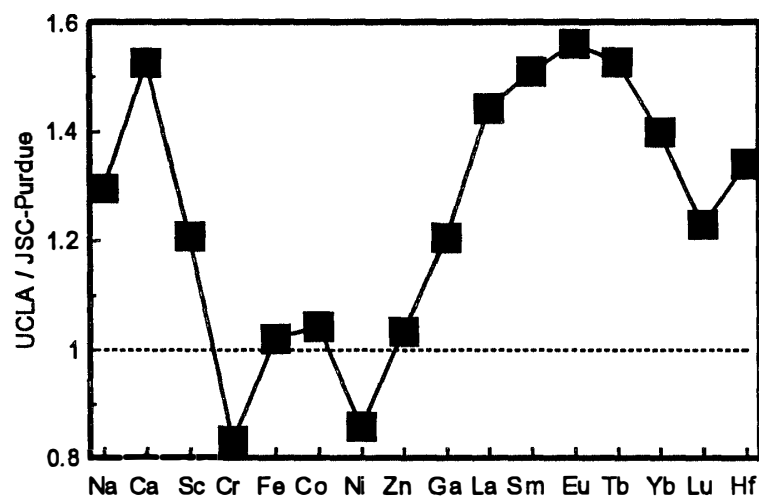

Fig. 4. Comparison of element compositions of the UCLA and JSC-Purdue samples. This diagram uses our preferred Co (INAA) and Zn (RNAA) data.

ple was considerably enriched in the incompatible lithophile elements, Na, Ca, REE and Hf.

4. Discussion

As mentioned in the introduction, Y-793605 is petrologically similar to two other martian meteorites, the lherzolites ALHA77005 and LEW 88516 (HARVEY *et al.*, 1993; IKEDA, 1994; LUNDBERG *et al.*, 1990; MCSWEEN *et al.*, 1979b; TREIMAN *et al.*, 1994). These rocks are believed to be partial cumulates, and hence do not represent liquid compositions (*e.g.*, MCSWEEN *et al.*, 1979b). As mentioned above, the largest of these rocks, ALHA77005, contains two distinct lithologies, called light and dark. The light lithology is the coarser-grained, poikilitic textured material, while the dark lithology is the finer-grained, interstitial textured material (LUNDBERG *et al.*, 1990). The interpretation of this petrologic distinction is that the light lithology represents cumulate minerals with minor trapped melt component, while the dark lithology is richer in the trapped melt component (LUNDBERG *et al.*, 1990). We will discuss the geochemistry of Y-793605 in the context of this petrologic model of martian lherzolites.

Throughout the discussion, we will be comparing Y-793605 to compositional data on ALHA77005 and LEW 88516. The data used in these comparisons come from our unpublished data on ALHA77005 (MITTLEFEHLDT and LINDSTROM), plus the following literature sources: CHEN and WASSERBURG (1986, 1993), DREIBUS *et al.* (1992), JAGOUTZ (1989), JAROSEWICH (1990), LAUL (1987), MA *et al.* (1981), MCSWEEN *et al.* (1979a), ONUMA and HIRANO (1981), SHIH *et al.* (1982), SHIMIZU and MASUDA (1981), SMITH *et al.* (1984), TREIMAN *et al.* (1994), WANG *et al.* (1997), WÄNKE *et al.* (1986), WARREN and KALLEMEYN (1996, 1997), YANAI and KOJIMA (1995).

4.1. Alteration phases

Some of the alteration phases present in Y-793605 seem likely to be the products of weathering while on Earth. The thin layer of silica on the exterior chip ,75, which contains minor, variable amounts of S, K, Fe, Al, and other elements, is relatively common on exterior surfaces of a variety of antarctic meteorites and is certainly of terrestrial origin (*e.g.*, WENTWORTH and GOODING, 1996). The other secondary mineral identified on the exterior surface, K-Fe-sulfate (probably jarosite), also is a common product of terrestrial weathering in antarctic meteorites. The interior sample (,10) also contains minor K-Fe-sulfate (Fig. 1A), but the most common alteration product is Fe-phosphate (Figs. 1B, 1C), some of which is texturally like that seen in martian lherzolite ALHA77005 (WENTWORTH and GOODING, 1993). The interior chip also contains what appear to be partly decomposed Ca-phosphate grains with highly pitted grain surfaces (Fig. 1D). At present, we cannot determine whether any of these alterations products are the result of martian weathering. We have not yet identified carbonates or Ca-sulfates in Y-793605. These latter phases are believed to be pre-terrestrial secondary minerals in some of the other martian meteorites, for example, Chassigny (WENTWORTH and GOODING, 1994), EETA79001 (GOODING *et al.*, 1988) and Nakhla (GOODING *et al.*, 1991). Pre-terrestrial secondary minerals are generally very rare in martian meteorites (with the exception of ALH 84001). Because we had only two small chips for study, and neither of these had fusion crust, we have not been able to do an exhaustive search for possible martian alteration products. Much more

work is needed to determine whether Y-793605 contains pre-terrestrial secondary phases.

The possibility that the Ca-phosphates are partially decomposed is worrisome. Phosphates in martian lherzolites contain a significant fraction of the total rock rare earth element (REE) content (*e.g.*, HARVEY *et al.*, 1993). Therefore, if the Ca-phosphates in the rock were significantly altered, either while on Mars or on the Earth, then the bulk rock REE contents could have been changed. This is observed in antarctic eucrites, where terrestrial weathering has resulted in extensive mobilization and loss or gain of REE, presumably by dissolution of Ca-phosphates (MITTLEFEHLDT and LINDSTROM, 1991). The basaltic eucrites show highly variable and anomalous REE patterns as a result. The fact that all three martian lherzolites are so similar in REE contents and patterns (see below, and WARREN and KALLEMEYN, 1997) suggests that REE mobilization has not been significant. We will assume for the remainder of this paper that the REE contents of the samples represent their original, igneous contents. Nevertheless, detailed study of Ca-phosphates in martian meteorites, especially the antarctic samples, should be done to investigate this further.

4.2. Incompatible lithophile elements

Our previous analyses of ALHA77005 light and dark lithologies demonstrated that the light lithology is poorer in incompatible lithophile elements than is the dark lithology (TREIMAN *et al.*, 1994). This is in accord with the petrologic scenario described briefly above; the light lithology, containing less of a petrologically identifiable trapped melt component, ought to be poor in incompatible lithophile elements. In Fig. 2 we show a REE diagram for Y-793605 and the other martian lherzolites. Also shown for comparison is an average of three xenoliths from EETA79001 lithology A (MITTLEFEHLDT and LINDSTROM, unpublished). The xenoliths in lithology A are believed to be fragments of a rock unit that was similar to the martian lherzolites (McSWEEN and JAROSEWICH, 1983; STEELE and SMITH, 1982).

Our glass-poor whole rock sample of Y-793605 is poor in the incompatible lithophile elements, such as the REE, and is comparable to the average of ALHA77005 light lithology (Fig. 2). Hence, our sample must be poor in the trapped melt component. Note, however, that the glass-rich sample contains higher concentrations of the REE than does ALHA77005 dark lithology (Fig. 2) We previously showed that a glass-rich sample of LEW 88516 contained higher concentrations of the incompatible elements than did a whole rock sample, and speculated that this suggested slight preferential impact melting of the trapped melt bearing portions of the rock (TREIMAN *et al.*, 1994). A subsequent measurement of glass-poor and glass-rich samples of LEW 88516 (WARREN and KALLEMEYN, 1996) showed that this is not a general feature, however. Also shown in Table 1 and Fig. 2 is an estimated bulk composition for Y-793605. This bulk composition was calculated by taking the average of our analyses, weighted by the masses of the glass-poor (~92%) and glass-rich (~8%) material in the sample. If the proportions of glass-rich and glass-poor material in Y-793605, 10-71 are representative of the rock as a whole, and if our analyses are representative of these materials, then Y-793605 is poorer in incompatible lithophile elements than are bulk ALHA77005 and LEW 88516 (Table 1 and Fig. 2). This then implies that Y-793605

contains less of a trapped melt component than do the other lherzolites. However, KOJIMA *et al.* (1997) estimate that the stone as a whole contains about 30 vol% glassy material. (The density difference between the glassy material and the bulk rock is likely small enough that vol% and wt% are directly comparable.) If this estimate is reasonably accurate, and if all the glass-rich material is similar in composition to the sample we measured, then bulk Y-793605 may be very similar to bulk ALHA77005 and LEW 88516 in composition.

WARREN and KALLEMEYN (1997) have analyzed another bulk sample of Y-793605 about half the mass of our total sample. Their results are compared to ours in Fig. 4 for the elements we determine in common, excluding Ir for which we have a fairly large analytical uncertainty (Table 1). The UCLA sample has similar contents of the compatible transition elements Cr, Fe, Co, Ni and Zn to our sample, although Cr and Ni are lower in the UCLA sample, while the most incompatible elements, Na, Ca, REE and Hf, were enriched in the UCLA sample. This indicates that the UCLA sample is richer in a trapped melt component containing the most incompatible elements. The compatible transition elements will largely be contained in the mafic cumulus phases, olivine, low-Ca pyroxene and chromite, and should be similar in the two samples because they dominate the bulk mineralogy. The slightly lower Cr and Ni in the UCLA sample may indicate heterogeneous distribution of minor phases; chromite and sulfides. As shown by WARREN and KALLEMEYN (1997), the UCLA sample of Y-793605 is close to the average compositions of ALHA77005 and LEW 88516.

In Fig. 5 we show a plot of CI chondrite-normalized La/Yb *vs.* Sm concentration for all available analyses of martian lherzolites and xenoliths from EETA79001 lithology A. On this diagram, Sm serves as an index of the amount of trapped melt contained in the samples; the higher the Sm concentration, the greater the amount of trapped melt. Note that different samples of ALHA77005 cover virtually the entire range of Sm contents found in the lherzolite samples, indicating that the Sm content is not being controlled by other factors, such as differences in parent melt composition.

We have drawn a model mixing line through the data in Fig. 5 which shows mixing between cumulus minerals and trapped melt. This is just a semi-quantitative calculation which is only meant to illustrate a point, not to attempt a quantitative model of the martian lherzolites. For this model, we assumed olivine and orthopyroxene are the only cumulus phases (*e.g.*, LUNDBERG *et al.*, 1990), and used modal data from TREIMAN *et al.* (1994) to estimate the proportions of olivine and orthopyroxene in the cumulate. We then assumed that the sample with the highest Sm content contains roughly 15% trapped melt. Using olivine/melt and orthopyroxene/melt partition coefficients from JONES (1995), we were then able to estimate the La, Sm and Yb contents of the cumulate and the trapped melt. The dashed line represents mixing between the cumulus minerals (low Sm, low La/Yb) and the trapped melt (high Sm, high La/Yb). As can be seen, the martian lherzolite samples lie along this mixing line and thus are consistent with the petrologic model that suggests they are partial cumulates containing trapped melt.

Three other points are worth noting in regard to Fig. 5: i) because the $(La/Yb)_{CI}$ ratios of the lherzolite whole rock samples are asymptotically approaching a value <1
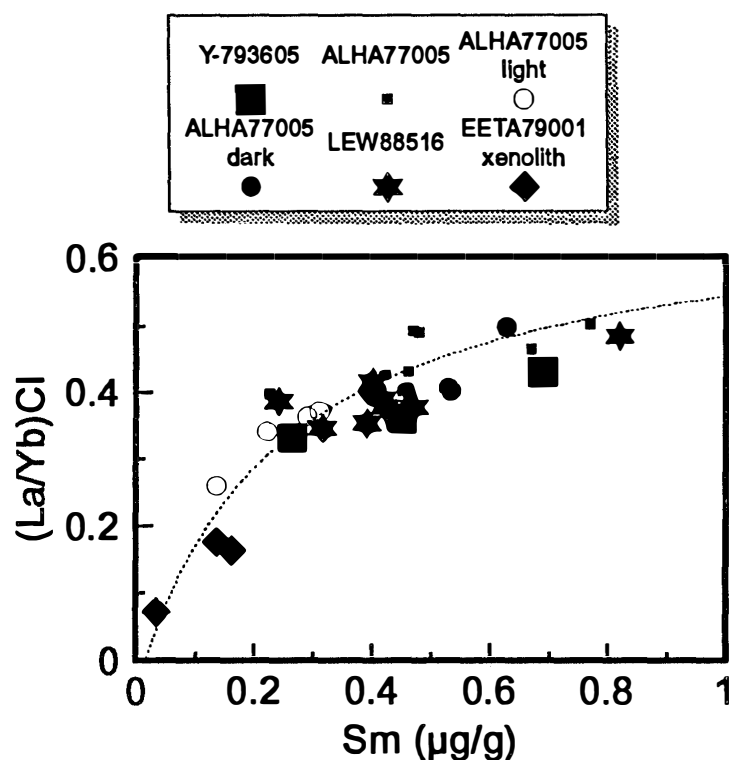
Fig. 5. CI chondrite-normatized La/Yb vs. Sm concentration for all available analyses
of martian lherzolites, plus xenoliths from EETA79001 lithology A. The dashed
line shows a mixing model between cumulus minerals and trapped melt.

with increasing Sm, the parent melt of the lherzolites was light-REE depleted. This
similarly was calculated by HARVEY *et al.* (1993) and LUNDBERG *et al.* (1990) from
their ion probe data. This is a geochemical characteristic shared with martian basalts
EETA79001 lithology B and QUE 94201 (*e.g.*, MITTLEFEHLDT and LINDSTROM, 1996).
ii) There is a relatively minor change in the $(La/Yb)_{CI}$ ratios of the samples with a
much larger change in the Sm content. This means that the incompatible trace ele-
ment contents of the samples are essentially dominated by the trapped melt compo-
nent, not the cumulus minerals. The REE patterns (though not the abundances) shown
in Fig. 2 are then close to those of the parent melts of the lherzolites. This was also
demonstrated by HARVEY *et al.* (1993) and LUNDBERG *et al.* (1990) for parent melts
of ALHA77005 and LEW 88516 calculated from their ion probe data on cumulus min-
eral grains. iii) The xenolith samples from EETA79001 lithology A are consistent with
the mixing model. This suggests that these xenoliths are from rock units generally
similar to the martian lherzolites, as first suggested by petrologic studies (MCSWEEN
and JAROSEWICH, 1983; STEELE and SMITH, 1982).

4.3. Volatile/mobile elements

Figure 3 is a plot of the CI chondrite-normalized volatile/mobile elements deter-
mined by RNAA in martian lherzolites and in all martian meteorites, plotted in order
of nebular volatility as estimated from thermodynamic calculations and by analyses
of chondritic meteorites. On this type of diagram, chondritic meteorites would show

a pattern of increasing depletion from U to In, as illustrated by the mean of all of our (LIPSCHUTZ and colleagues) analyses of the CV chondrite Allende. This type of pattern represents what one would expect of materials formed solely by nebular processes. To a first approximation, the bulk compositions of planets should show this type of volatility-controlled depletion pattern (e.g., WÄNKE, 1987). Deviations from this pattern for planetary materials (basalts, lherzolites, etc.) reflect geochemically-controlled fractionations, such as lithophile elements from siderophile elements and incompatible elements from compatible elements.

As can be seen (and as expected) in Fig. 3, martian lherzolites do not follow a volatility controlled depletion pattern. The elements that are substantially lithophile in character, U, Ga, Rb, Cs and Zn, have generally the highest abundances in martian lherzolites. There is a general trend of increasing depletion with increasing nebular volatility among these five elements. This is a signature of the general volatile depletion pattern of Mars (LONGHI et al., 1992) that has not been entirely obscured by planetary differentiation processes. Indium is also relatively abundant in the lherzolites and in all martian meteorites compared to elements of similar volatility (Bi, Tl). This suggests that In may also be substantially lithophile in character on Mars, while Bi and Tl are not.

The remainder of the elements shown in Fig. 3 are siderophile or chalcophile elements. Their depletions below a plausible volatility-controlled depletion pattern undoubtedly reflect sequestration in the core of Mars during planetary scale differentiation. Cobalt is enriched in the lherzolites compared to other siderophile and chalcophile elements (e.g., compare with Au and Sb). Cobalt is partially lithophile in character, and is compatible in mafic minerals such as olivine and orthopyroxene (e.g., JONES, 1995). Hence, an ultramafic partial cumulate like the martian lherzolites can be expected to show an enrichment in Co compared to other, more highly siderophile elements, such as Au and Sb. Note that the Purdue Co data were used in this figure, and may be systematically low (discussed above). Therefore, Co may be even more anomalous compared to other siderophile elements than this diagram indicates.

5. Conclusions

Our preliminary SEM studies have identified several alteration phases on both exterior and interior chips. Some of them are most likely the results of weathering on Earth. So far, we have not identified any alteration phases that must be martian in origin, but much more work is needed to establish the paragenesis of these phases. The partially decomposed Ca-phosphates deserve particular attention because of the potential implications for affecting the original REE, Th and U contents of bulk rock samples.

Yamato-793605 is compositionally similar to the other martian lherzolites ALHA77005 and LEW 88516 for a wide range in lithophile, siderophile and chalcophile elements. The compositions of these rocks are consistent with petrologic information which suggests that they are mixtures of cumulus minerals and trapped, intercumulus melt. Compared to the other lherzolites, our sample of Y-793605 is generally poorer in the incompatible lithophile elements, suggesting that it contains less of

the trapped melt component. However, because Y-793605 is a small stone, and because the martian plagioclase lherzolites are heterogeneous, we can't claim that the rock unit it came from was generally lower in a trapped melt component than was the rock unit that provided the other lherzolites. This is born out by the analyses of the UCLA sample, which is very similar to the other lherzolites (WARREN and KALLEMEYN, 1997). Indeed, the three martian lherzolites are so similar that it is quite plausible that they all came from the same rock unit on Mars, quite possibly only a few tens of centimeters apart. Individual analyses of ALHA77005 exhibit differences in incompatible element contents by factors of 2–3, which shows that sample heterogeneity in the lherzolites is extensive. Our sample of Y-793605 falls within the range of analyses of ALHA77005.

Acknowledgments

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