

YAMATO-793605, EET79001, AND OTHER PRESUMED MARTIAN METEORITES: COMPOSITIONAL CLUES TO THEIR ORIGINS

Paul H. WARREN^{1,2} and Gregory W. KALLEMEYN^{1,3}

¹*Institute of Geophysics and Planetary Physics,
University of California, Los Angeles, CA 90095-1567, U. S. A.*

²*Mineralogical Institute, Graduate School of Science,
University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113*

³*Department of Chemistry, Faculty of Science, Tokyo Metropolitan University,
1-1, Minami-Ohsawa, Hachioji-shi, Tokyo 192-03*

Abstract: We report new data on the bulk compositions of several martian meteorites, most notably the Y-793605 peridotite. We find that Y-793605 is remarkably similar in composition to the other shergottitic peridotites, ALH77005 and EET79001. This high degree of compositional uniformity, and analogy to terrestrial ultramafic cumulates, suggest that the three peridotites formed in the comparatively uniform early-middle (and thus deep) portion of a martian layered intrusion. Considering that the process of launching off Mars probably required that a prior impact excavated these originally deep materials to positions closer to the surface, their compositional uniformity seems improbable, unless they were originally launched as a single mass that shortly thereafter underwent a secondary collisional fragmentation in the asteroid belt. We interpret "A" lithology of EET79001 as more likely to be an endogenously produced mixed magma than an impact melt. Our results indicate that Au is only slightly enriched in EET79001-A, compared to EET79001-B. The EET79001-A lithophile element composition can only be roughly approximated by modeling it as a mixture of EET79001-B plus any known variety of shergottitic peridotite, and the Au contents of martian meteorites (in general) are highly diverse. The presence of only two grossly dissimilar rock types (EET79001-B and EET79001-"X") as discernible components in EET79001-A seems an unlikely outcome from the chaotic process of impact mixing. Moreover, in general, it seems improbable that one of only 12 martian meteorites would be an impact melt of relatively young age.

1. Introduction

An abundance of evidence indicates that a petrologically diverse group of meteorites, presently numbering 12 and sometimes called the SNC meteorites, are transported pieces of the igneous crust of Mars (MEYER, 1996). The case for martian provenance was recently strengthened by the discovery of abundant preterrestrial carbonates in ALH84001 (MITTFELDLT, 1994; MCKAY *et al.*, 1996). For purposes of discussion, we presume that all 12 meteorites of this group are martian.

One of the most recently discovered martian meteorites is the 17 g Yamato-793605 peridotite (YANAI, 1995; MIKOUCHI and MIYAMOTO, 1997). As members of the consortium organized to study Y-793605 by the NIPR (KOJIMA *et al.*, 1997), we are inves-

tigating the concentrations of a variety of trace elements as well as major elements in the meteorite's bulk composition. We also report new data for several other martian meteorites: the ALH77005 shergottitic peridotite, which is similar to Y-793605, the lithologically complex shergottite EET79001, the ALH84001 orthopyroxenite, and the QUE94201 shergottite (MEYER, 1996). We discuss the implications of these new data, particularly with regard to suggestions (*e.g.*, WADHWA *et al.*, 1994; MITTLEFEHLDT *et al.*, 1997a) of a close connection between shergottitic peridotites, similar to Y-793605, and EET79001.

Although Y-793605 and the similar martian meteorites ALH77005 and LEW88516 are commonly described as lherzolites, petrographic studies have discovered abundant clinopyroxene but no definite orthopyroxene, except where formed by slight subsolidus exsolution, in any of these rocks (*e.g.*, ISHII *et al.*, 1979; HARVEY *et al.*, 1993; IKEDA, 1994; TREIMAN *et al.*, 1994; MIKOUCHI and MIYAMOTO, 1997). Original igneous crystallization of some pyroxene as orthopyroxene has only been inferred, based on compositional data for what is presently pigeonite, for ALH77005 (ISHII *et al.*, 1979). According to standard igneous nomenclature, a lherzolite must have $\text{opx}/(\text{ol} + \text{opx} + \text{cpx}) > 5\%$. Peridotite with $\text{opx}/(\text{ol} + \text{opx} + \text{cpx}) < 5\%$ is properly termed wehrlite. Until more definite evidence for orthopyroxene becomes available, we prefer to describe these samples as generic peridotites.

2. Analytical Procedures

All samples were prepared for instrumental neutron activation analysis (INAA) by crushing to powder using an agate mortar and pestle in our clean room at UCLA. The consortium allocated for our study of Y-793605 a 208 mg aliquot from a powder that originally weighed 308 mg. The other 100 mg of this powder was sent (for a similar INAA-based study) to T. FUKUOKA. This powder was produced by crushing a mix of solid material dominated by a single 285-mg piece, plus numerous small crumbs (of nondescript appearance) produced during the splitting of the 2-g sample Y-793605,10. The proportion of dark glassy matter in the material that contributed to this powder was estimated at roughly 10%, *i.e.*, roughly $0.3 \times$ the estimated average for the meteorite. After INAA, we further subdivided the 208 mg powder into a 191 mg aliquot for future radiochemical neutron activation analysis (RNAA) plus a 17 mg aliquot for microprobe fused bead analysis (MFBA).

Samples of ALH77005, ALH84001, EET79001, and QUE94201 were crushed to powders in agate, then divided (before INAA) into large aliquots for neutron activation analysis plus aliquots of 15–25 mg for MFBA. The MFBA technique, performed on UCLA's Camebax EPMA running with four wavelength-dispersive spectrometers, is our only source of data for Si, our primary source for Mg, and provides a useful check on INAA for Al, Ca, Ti, Cr, Mn and Fe. Our INAA procedure has been described by KALLEMEYN (1993). In general, we also utilize the INAA powder for subsequent RNAA, to determine Ni, Zn, Ge, Cd, Re, Os, Ir and Au. Two of these elements (Ni, Zn) are also typically determined well by INAA, and Au is in some cases marginally determined by INAA. Thus far, however, RNAA has only been applied to ALH84001 and ALH77005, and those data have been reported previously (WARREN

and KALLEMEYN, 1996).

We studied EET79001 starting with two separate 0.65-g solid pieces, one each from lithology A and lithology B (see MEYER, 1996, for review of descriptions of these texturally and mineralogically distinct domains). We subdivided each of these original allocations into two subequal masses before crushing them to powders. Thus, we studied (INAA+MFBA+future RNAA) a total of four separate EET79001 powders. We started with similarly large allocations of ALH77005 and ALH84001, but in these cases we elected to produce only one powder of each meteorite, from which aliquots were taken for: one INAA, one (*separate* powder aliquot) RNAA, plus one MFBA for ALH77005; and two INAA, two RNAA, and one MFBA for ALH84001.

3. Results

3.1. Yamato-793605

Results are shown in Table 1. Our data confirm previous indications (YANAI, 1995; MIKOUCHI and MIYAMOTO, 1996) that Y-793605 is a peridotite remarkably similar to ALH77005 and LEW88516. The degree of similarity is illustrated in Figs. 1 and 2, where the Y-793605 composition is shown normalized to the average for the three peridotites (including Y-793605). All these rocks are poikilitic textured igneous cumulates (HARVEY *et al.*, 1993; TREIMAN *et al.*, 1994; MIKOUCHI and MIYAMOTO, 1997), and thus probably formed in a layered intrusion. The Y-793605 composition shows indications of a lower trapped liquid content. The plagiophile elements Na and Al, plagiophile/incompatible element K, and highly incompatible element La, all are depleted by small factors in Y-793605 compared to the peridotite average. Results from other pieces of Y-793605 (EBIHARA *et al.*, 1997; MITTFELDLT *et al.*, 1997b)

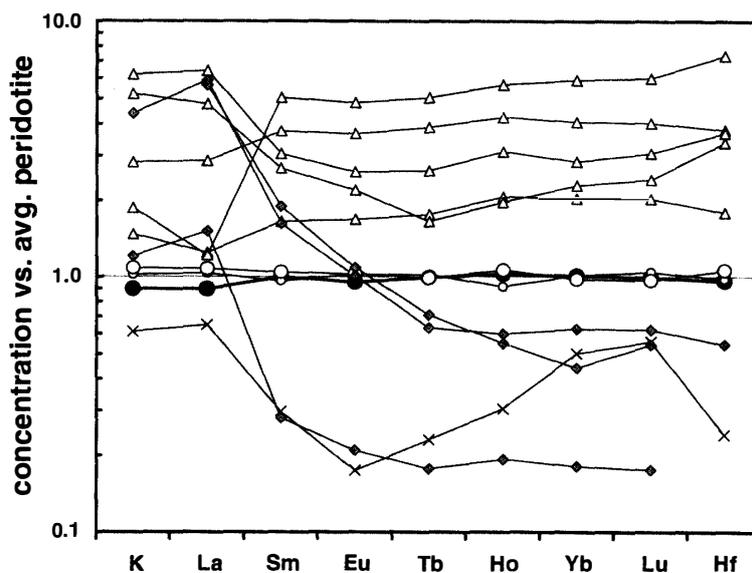


Fig. 1. Bulk compositions of Y-793605 and two other martian peridotites, normalized to the trio average (Table 1), illustrating compositional uniformity. Literature averages for shergottites (triangles), nakhlites and Chassigny (diamonds) and ALH84001 (\times) are shown for comparison.

Table 1. Bulk compositions of presumed martian meteorites determined by INAA, MFBA and RNAA.

	mass mg	Na mg/g	Mg mg/g	Al mg/g	Si mg/g	K µg/g	Ca mg/g	Sc µg/g	Ti mg/g	V µg/g	Cr mg/g	Mn mg/g	Fe mg/g	Co µg/g	Ni µg/g	Zn µg/g	Ga µg/g	Ge ng/g	Se µg/g	Rb µg/g	Sr µg/g	Zr µg/g
normal uncertainty*		3%	4%	4%	3%	7%	3%	3%	5%	5%	4%	3%	4%	3%	5%	6%	6%	9%	8%	---	8%	8%
ALH77005,128 notable uncertainties*	615	3.29	175	16	193	220	21	19.0	<5	166	7.0	3.40	159	78	310	59	6.9	580	0.04	<4.2	<20	<30
ALH84001,56a notable uncertainties*	337	1.05	149	6.4	247	127	13.0	11.8	1.19	205	7.3	3.64	134	45	5.8	90	2.74	1080	<0.17			
ALH84001,56b notable uncertainties*	332	1.12	149	6.4	247	122	12.9	13.1	1.19	205	8.0	3.63	135	50	<20	92	2.3		<0.23	<7.8	<24	<38
EET79001,397a (lithol. A) notable uncertainties*	312	6.6	72	38	241	330	61	37.2	5.7	230	4.29	3.66	130	43	128	85	14.2			<6.9	<46	67
EET79001,397b (lithol. A) notable uncertainties*	321	5.9	88	31	236	320	53	38.0	4.2	220	4.76	3.81	144	55	179	65	12.8		<0.53	<4.3	<59	44
EET79001,399a (lithol. B) notable uncertainties*	319	13.2	33	62	232	660	78	43.2	9.2	159	0.65	3.20	137	27.7	23	105	26.8			<6.9	34	64
EET79001,399b (lithol. B) notable uncertainties*	324	15.1	31	71	233	650	77	42.1	7.5	135	0.42	3.16	132	28.4	19	92	29.9	1.83		<4.1	28	90
QUE94201,19 notable uncertainties*	305	10.3	38	52	224	320	82	49.0	11.9	124	1.01	3.65	149	24.4	<40	108	25.9			<6	59	94
Y793605,10 notable uncertainties*	310	2.63	158	12.3	212	204	29	25.0	2.1	202	6.9	3.70	153	72	280	49	6.8		<0.42	<1.3	<44	<63
Literature avg. ALH77005		3.38	170	15.5	199	230	23.5	21.3	2.57	162	6.9	3.50	156	72	333	60	6.8	580	0.10	0.75	14.3	19.5
Literature avg. LEW88516		3.53	150	13.1	219	230	31.1	25.8	2.02	179	6.0	3.72	153	63	256	58	7.6	520	0.32	0.40	22	17.2
Avg. 3 shergottitic lherzolites		3.18	159	13.6	210	220	27.8	24.0	2.25	181	6.6	3.64	154	69	289	56	7.1	550	0.21	0.58	18	18.4
Literature avg. EET79001-A		6.4	93	31.2	233	340	52	36.7	4.2	217	4.3	3.73	143	48	150	72	13.2		0.47	1.04	53	56
Literature avg. EET79001-B		12.8	40	58.4	231	640	77	47.3	7.4	177	1.0	3.31	136	30	28	94	24.5		0.88	1.78	47	77

These data for QUE94201,19 supercede the preliminary data set published by Warren et al. (1996).

Averages shown for shergottitic lherzolites ALH77005 and LEW88516 are based on a comprehensive compilation of literature data, mainly from sources cited in Meyer (1996); data for ALH77005,128 shown above were included for the ALH77005 average.

* Uncertainties in INAA counting statistics are shown where they are large in comparison to normal 70% confidence levels (i.e., "normal" for moderate-high concentrations).

Table 1 (Continued).

	Cd	Cs	Ba	La	Ce	Nd	Sm	Eu	Tb	Dy	Ho	Yb	Lu	Hf	Ta	Re	Os	Ir	Au	Th	U
	ng/g	ng/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	pg/g	pg/g	ng/g	pg/g	μg/g	μg/g
normal uncertainty*	8%	9%	8%	4%	7%	8%	4%	4%	6%	9%	7%	5%	5%	6%	10%	6%	5%	5%	6%	7%	9%
ALH77005,128 notable uncertainties*	2.1 34%	<90	<18	0.40	<2.5	<0.9	0.48	0.25	0.17	1.04	0.23 15%	0.57	0.085	0.57	0.04 30%	102	4400	4.1	260	<0.1	<0.06
ALH84001,56a notable uncertainties*	77			0.246	0.65 12%		0.160	0.049	0.043 20%	<0.56		0.262	0.042	0.117	<0.042	1.66 15%	10.2 7%	0.08	9.4	<0.05	<0.3
ALH84001,56b notable uncertainties*		<50	<28	0.28	0.70 9%	<0.9	0.163	0.045	0.042 21%	0.3 40%	0.070 14%	0.30	0.050	0.111 18%	<0.06			<2.2	<640	0.11 24%	<0.03
EET79001,397a (lithol. A) notable uncertainties*		<103	<26	0.48	1.71 25%	<1.2	0.78	0.40	0.32	2.1 37%	0.40 15%	1.16	0.17	0.97	<0.08			<2.3	<2000	<0.10	<0.16
EET79001,397b (lithol. A) notable uncertainties*		<120	<18	0.41	1.13 13%	<2.6	0.76	0.37	0.32	2.2 38%	0.49 8%	1.11	0.16	0.98	0.03 39%			<5	960 35%	<0.07	<0.04
EET79001,399a (lithol. B) notable uncertainties*		159 14%	<50	1.18	2.63 8%	2.55 35%	2.01	0.96	0.76	5.2 16%	1.09 11%	2.61	0.40	2.26	0.09 14%			<1.3	<1000	0.14 22%	<0.24
EET79001,399b (lithol. B) notable uncertainties*		<130	<26	1.03	2.34	3.1 11%	1.95	0.95	0.79	5.1 20%	1.08 8%	2.65	0.38	2.31	0.068			<2.4	<200	0.15 11%	<0.07
QUE94201,19 notable uncertainties*		<120	<41	0.44	1.63 12%	2.36 30%	2.55	1.09	0.934	6.1 14%	1.32 9%	3.5	0.537	3.4	<0.08			<2.4	<500	<0.09	<0.2
Y793605,10 notable uncertainties*		<123	<17	0.29	0.84 31%	<0.12	0.45	0.206	0.168 7%	<1.6 15%	0.234	0.56	0.080	0.51	<0.04			3 35%	<800	<0.06	<0.05
Literature avg. ALH77005	6	39	5.1	0.35	0.94	0.88	0.46	0.295	0.168	1.07	0.24	0.55	0.078	0.58	0.032	102	4400	4.3	280	0.056	0.014
Literature avg. LEW88516	12.4	49	4.9	0.33	1.60	0.82	0.43	0.222	0.173	1.04	0.21	0.56	0.084	0.52	0.032	75	2550	2.4	440	0.060	0.015
Avg. 3 shergottitic lherzolites	9.2	44	5.0	0.32	1.13	0.85	0.45	0.241	0.170	1.054	0.23	0.56	0.081	0.54	0.032	88	3500	3.2	360	0.058	0.015
Literature avg. EET79001-A	37	73	<10	0.40	1.33	1.35	0.74	0.36	0.28	2.02	0.47	1.12	0.165	0.95	0.027			<2	?	0.080	0.019
Literature avg. EET79001-B	70	140	13.0	0.87	2.28	2.70	1.61	0.76	0.61	4.3	0.97	2.17	0.31	1.94	0.079			<2	?	0.135	0.037

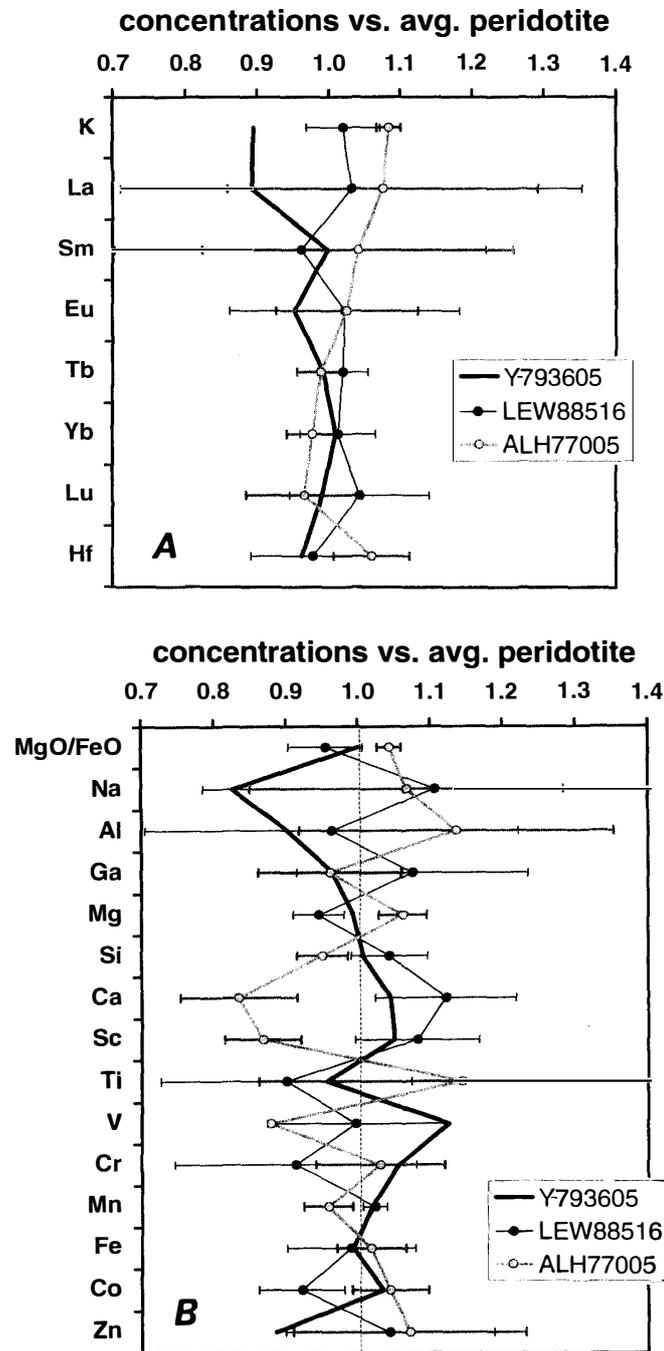


Fig. 2. Bulk compositions of Y-793605 and two other martian peridotites, normalized to the trio average (Table 1), illustrating compositional uniformity. Error bars for ALH77005 and LEW88516 represent average \pm one standard deviation for the literature database (which includes our new data in Table 1). (A) Rare-earth elements, K and Hf; and (B) other elements, are shown in sequence by atomic number, except three plagiophile elements (Na, Al and Ga) are grouped together near the top.

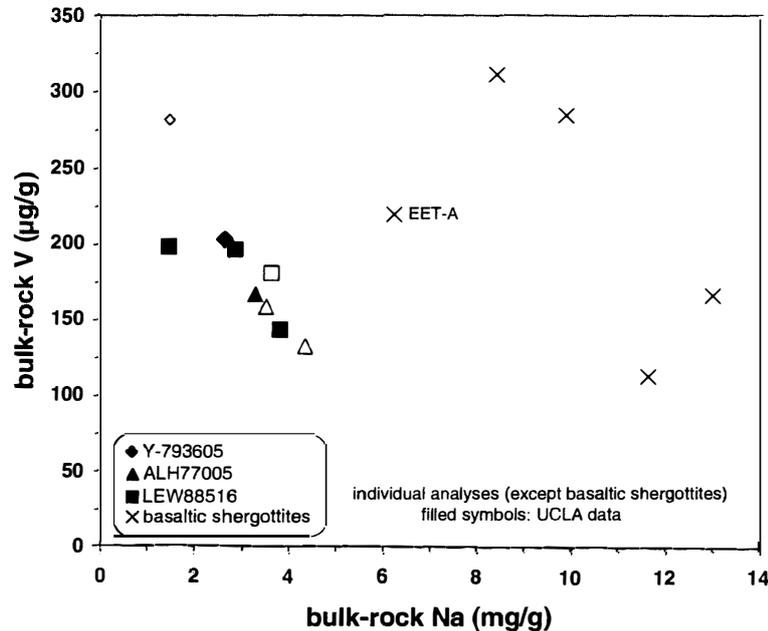


Fig. 3. Results including all three shergottitic peridotites show a consistent anticorrelation between plagiophile/incompatible element Na and pyroxene/chromite-compatible element V. Black-filled symbols represent UCLA data (WARREN and KALLEMEYN, 1996, and Table 1 of this work), open symbols represent data from other labs (MA *et al.*, 1981; DREIBUS *et al.*, 1992; EBHARA *et al.*, 1997). Variations shown are probably mainly due to real heterogeneities within the martian meteorites, not inter-laboratory bias. The biggest scatter off the trend is for a tiny (61 mg) Na- and V-poor subsample of LEW88516 (WARREN and KALLEMEYN, 1996). Literature averages for "basaltic" shergottites (Shergotty, Zagami, EET79001-A, EET79001-B and QUE94201) are shown for comparison.

show slightly greater relative depletions for these elements. However, comparable depletions have been observed previously in the "light" component of ALH77005 (JAROSEWICH, 1990; TREIMAN *et al.*, 1994), and in a small (61 mg) subsample of LEW88516 (WARREN and KALLEMEYN, 1996). The relative depletions of these elements in Y-793605 appear to be part of a consistent trend of variations, common to subsamples of Y-793605, ALH77005 and LEW88516 (Figs. 3, 4), and such a trend could plausibly form, primarily by variations in trapped liquid content, and secondarily by variations in cumulus mineral proportions, during accumulation from a single parent magma.

3.2. Other martian meteorites

Considering the splotchy cm-scale ("light" and "dark") heterogeneity of ALH77005 (MEYER, 1996), our data agree remarkably well with the literature average (Table 1). Our new data for ALH84001 agree well with our first analysis, and with literature data of MITTLFEHLDT (1994) and DREIBUS *et al.* (1994). Comparison between our data for EET79001 lithology A, especially the EET79001,397a sample, versus the literature average for this lithology (Table 1), suggests that our sample was relatively poor in the peridotitic (Mg- and Fe-rich, Na-, Al- and Ca-poor) xenocryst-

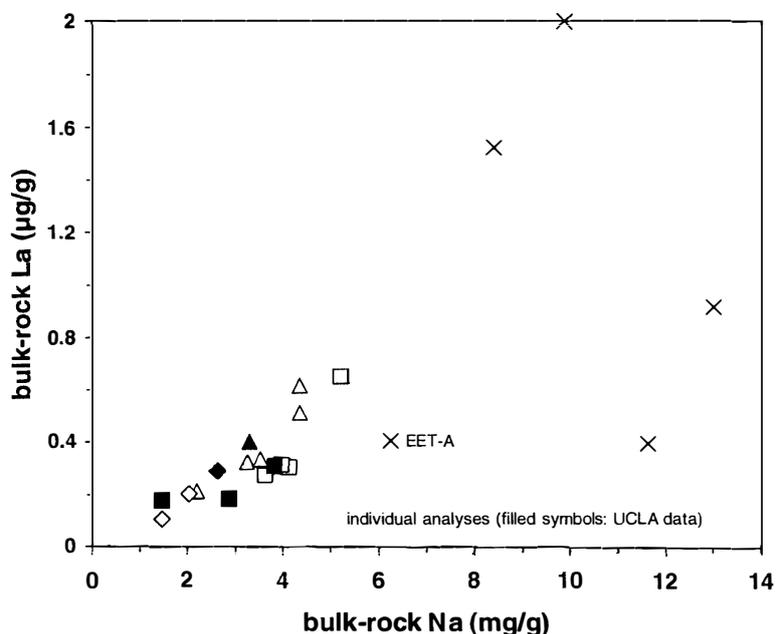


Fig. 4. Results including all three shergottitic peridotites show a consistent correlation between plagiophile/incompatible element Na and incompatible light rare-earth element La. Symbols and data sources are same as for Fig. 3, plus MITTLEFEHLDT *et al.* (1997b) and other sources cited by MEYER (1996). Literature averages for "basaltic" shergottites are shown for comparison.

tic materials that TREIMAN (1995) has called "lithology X". Our EET79001 lithology B samples also appear to have been relatively mafic-poor, compared to analyses previously published in the literature. These mild heterogeneity effects are not surprising, considering that the EET79001-A lithology is a complex mixture (MCSWEEN and JAROSEWICH, 1983; TREIMAN, 1993), and the EET79001-B lithology is comparatively coarse-grained. Significantly lower results for Na and Al in our QUE94201 analysis, compared to two literature analyses (DREIBUS *et al.*, 1996; KRING *et al.*, 1996), are presumably due to a slightly lower plagioclase content in our sample.

4. Discussion

4.1. Status of the Ga–Al correlation for martian meteorites

The martian meteorites are distinctive in many ways. One of the more convenient ways of assessing possible genetic relationships among meteorites is by comparison of element/element ratios that show consistency among individual suites, despite diversity among meteorites collectively. The ratio Ga/Al is a prime example, probably because Ga was more volatile than Al in the solar nebula, and yet once incorporated into a planet, Ga and Al are geochemically coherent (mainly because both are plagiophile). However, Ga shows only a very weak correlation with Al among lunar samples (HASKIN and WARREN, 1991). Our new data reinforce the evidence for a remarkably strong correlation between Ga and Al among all martian meteorites (Fig. 5). This correlation implies a bulk-Mars Ga/Al ratio of 0.0005, confirming other evidence that

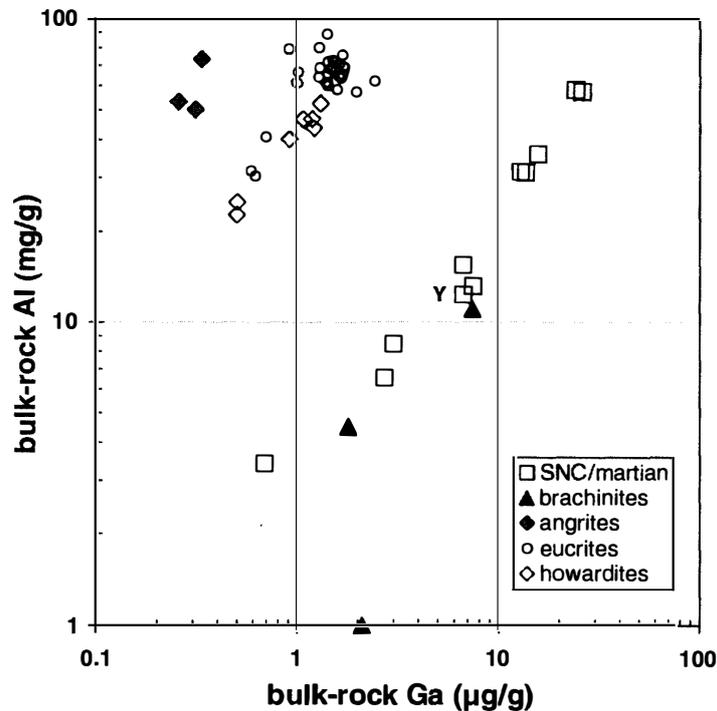


Fig. 5. Our new data reinforce the remarkably strong correlation between Ga and Al among martian meteorites ("Y" is Y-793605).

Mars is intermediate in volatile content between Earth and volatile-poor objects like the Moon and the HED parent asteroid (WÄNKE and DREIBUS, 1988).

4.2. Origin of Y-793605 and the other two peridotites

All three of the martian peridotites have cosmic-ray exposure (CRE) ages of ~ 3.7 Ma (EUGSTER and POLNAU, 1997), and this age is generally assumed to record the complete duration of the journey from Mars to Earth (*e.g.*, GLADMAN, 1997). However, at least two of the peridotites, ALH77005 and LEW88516, apparently did not reach Earth at the same time (JULL *et al.*, 1994; and other references in MEYER, 1996). The terrestrial age of Y-793605 has not yet been determined, but the great distance between the Yamato Mountains and the U.S. collecting areas on the opposite side of Antarctica (~ 3000 km) would ordinarily lead to a presumption against pairing. Assuming two separate peridotite fall events, they represent 2/12 of all martian meteorites; assuming three separate peridotite fall events, they represent 3/12. These admittedly poor statistics suggest that the 3.7 Ma event was a very rare event, responsible for a major fraction of all martian meteoroids currently in near-Earth space.

The degree of compositional coherency among the three martian peridotites (Figs. 1–4) is suggestive of derivation not only from a single layered intrusion, but from the same small region in the intrusion. Peridotitic portions of terrestrial layered intrusions typically feature systematic heterogeneity at all scales down to cm (*e.g.*, JACKSON, 1961). In the peridotitic portions of the Great Dyke, WILSON (1996) has noted "hundreds or even thousands of layers in a single outcrop". Aside from such small-scale

mineralogical/textural layering, if crystals are accumulating, and thus becoming removed from equilibration with the main mass of melt, at an efficiency of $\gg 50\%$, the melt composition inevitably must evolve as a result. The evolution is sharpest for elements with bulk solid/melt distribution coefficients $\ll 1$ or $\gg 1$, and the melt composition evolves most dramatically, in relation to the absolute mass of new crystals being formed, towards the final stages of the fractional crystallization process.

CANN (1982) showed that the equation for the concentration C_m of an element in the melt is

$$\frac{C_m}{C_0} = F^{\left[\frac{D+q+1}{q+1}\right]},$$

where C_0 is the concentration in the initial melt, q is the mass ratio of crystals precipitating to trapped liquid, F is the fraction of the main mass of melt remaining, and D is the bulk solid/melt distribution coefficient. As an example, consider the ratio in the melt of an incompatible element with $D=0.05$ to a compatible element with $D=2$, evolving in an intrusion with a moderate-high trapped liquid content (by terrestrial cumulate standards) of 30 wt%. As illustrated by Fig. 6, the incompatible/compatible ratio increases by a factor of only 1.36 over the first 20% of crystallization, but the rate of increase is enhanced as F diminishes, so that the incompatible/compatible ratio increases by a factor of 2.58 over the fourth 20% (*i.e.*, 60–80%) of crystallization, and in principle it increases by a further factor of 2.58 for each further diminution in F by a factor of 2 (*e.g.*, in going from 80 to 90% crystallization, from 90 to 95% crystallization, and so on). This effect may be partly offset by mixing of fresh pulses of magma into the residual melt. But as a rule, ignoring fine-scale modal lay-

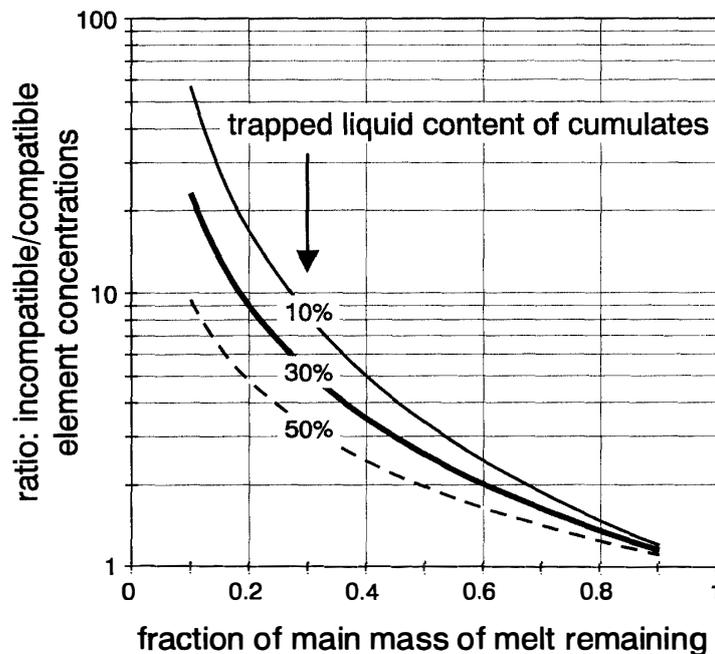


Fig. 6. Evolution of the ratio of an incompatible element ($D=0.05$) to a compatible element ($D=2$) during crystallization of cumulates in a layered intrusion, based on the CANN (1982) equation; shown for trapped liquid contents of 10, 30 and 50 wt%.

ering caused by uneven crystal accumulation (*e.g.*, uneven gravitational settling), layered intrusions are most heterogeneous near their last-crystallized regions (close to their tops, where exposed), and most homogeneous in their middle-deep interiors (CAWTHORN, 1996). Unless the three martian peridotites were originally only a few cm or meters apart, they probably all formed in a deep interior portion of the parent intrusion.

Also strongly suggesting derivation of the three peridotites from the lower portion of the parent intrusion are the consistent absence of cumulus plagioclase, and the compositions of melt inclusions in olivines, both indicating that the parent magmas were primitive in the sense of being too poor in Al_2O_3 to be plagioclase-saturated. Melt inclusion compositions in ALH77005 and LEW88516 suggest that the parent magmas had only about 6 wt% Al_2O_3 (LONGHI and PAN, 1989; HARVEY *et al.*, 1993). During crystallization of cumulus olivine, chromite, and Al-poor pyroxene, aluminum will behave essentially as an incompatible element, *i.e.*, it will nearly double in concentration with each halving of the residual melt volume. Unless the ultimate parent magma was extremely Al-poor, by the time the upper part of the intrusion formed, the melt should have had $\gg 6$ wt% Al_2O_3 .

Models of launch off a large body such as Mars or the Moon suggest that near-surface regions are strongly favored as the immediate pre-launch source locations of martian meteoroids (MELOSH, 1989). As reviewed by WARREN (1994), the 2π CRE records of lunar meteorites, generally indicating pre-launch depths of roughly 0.1–1 m, appear to confirm the strong advantage of a shallow pre-launch location. The martian meteorites consistently lack CRE evidence for launch from depths $\ll 5$ m, but on Mars, materials at very shallow depths may be too weathered to survive the violent launch process. On balance, therefore, the pre-launch depths were probably of the order 10 m (*i.e.*, $\gg 1$ m, but also not $\gg 10$ m). Assuming an igneous crystallization age of roughly 170 Ma (data for ALH77005: SHIH *et al.*, 1982; JAGOUTZ, 1989), there has been little opportunity for endogenous martian geologic activity to expose an originally deep region of the intrusion. Thus, if the original depth of formation was $\gg 10$ m, then these materials were probably excavated to their pre-launch location(s) by a prior impact. Impacts are presumably not much more common, in terms of craters of a given size per year, on Mars than on Earth. As reviewed by TREIMAN (1995), models range from roughly $1\times$ to $4\times$ the terrestrial rate. Thus, impact excavation has been a very rare process on Mars over the last 170 Ma. However, it may be almost a requirement for launch off Mars, if materials at very shallow depths are otherwise mostly too weathered to survive the violent delivery (launch and Earth atmospheric passage) process.

If a prior impact excavation is invoked, the ejecta from this impact should have been a jumbled mass of materials from many different regions of the parent intrusion. It is all the more remarkable, then, that these three cumulate peridotites, constituting the entire membership of the 3.7 Ma CRE cluster, are so nearly identical. Related but more evolved (or otherwise dissimilar) cumulates of the same intrusion should have been launched from the 3.7 Ma crater.

As an alternative to the prior impact excavation hypothesis, it might be assumed that the parent intrusion was so small that even at their original depth, these rocks

were shallow enough to be launched off Mars. However, considering that they probably originated relatively deep in the cumulate pile (as argued above), this model implies that the entire intrusion was never more than a few tens of meters thick. In that case, by analogy with terrestrial intrusions (and Fig. 6), the production of cumulates such as these would inevitably have engendered gross compositional heterogeneity, especially horizontal layering, at a scale of the order 1/10 of the intrusion thickness, i.e., at a scale of meters. Again, the detailed scenario seems improbable for launch of these three nearly identical rocks as separate meteoroids.

WETHERILL (1984) and GLADMAN (1997) have argued that martian meteorites are unlikely to reach Earth *via* secondary collisions after leaving Mars. These authors are certainly correct in rejecting, based on uniformly young CRE ages and especially the consistent lack of 2π CRE, the once-popular model that many if not all of the martian meteorites were launched off Mars from a 180-Ma crater and then shielded for 160–170 Ma from CRE within one or more large meteoroids (VICKERY and MELOSH, 1987). However, it still seems possible that a considerable portion of the total martian meteorite population represents secondary fragmentation products. GLADMAN's (1997) precise modeling of the dynamical evolution of meteoroids launched off Mars shows that roughly 20% of them quickly (time scale of order 0.2 Ma) migrate into the inner portion of the asteroid belt, where they should have significant probability for collisions with other asteroids (in this analysis of GLADMAN's (1997) results, we define the asteroid belt not simply on the customary basis of semimajor axis; the region of high asteroid density extends to significantly smaller heliocentric distances—we assume 2.0 AU—because most asteroid orbits are moderately eccentric). Assuming the primary meteoroid was too small to engender 2π CRE in most of the meteoroid's volume, and that the combined duration of the trip to the asteroid belt and the subsequent journey of the collisional fragment to Earth took ~ 3.7 Ma, then the CRE records would not show any significant difference *vs.* meteorites of more direct Mars–Earth derivation. Martian meteorites derived from secondary collisions might be expected to be generally smaller than other martian meteorites. Compared to the average martian meteorite mass of 4.0 kg (MEYER, 1996), LEW88516 (13 g) and Y-793605 (16 g) are tiny, and ALH77005 (482 g) is very small. Considering the extreme compositional-petrologic similarity among these three stones, for them the secondary fragmentation model seems slightly more plausible than alternative scenarios not invoking secondary fragmentation.

One advantage of assuming that a major portion of the total martian meteoroid population represents secondary fragmentation products, is that it helps to account for the enigmatically high ratio of martian to lunar meteorites (WARREN, 1994). Meteoroids of lunar derivation have very low probability of reaching Earth via any portion of the asteroid belt (GLADMAN *et al.*, 1995), so clearly, virtually no lunar meteorites are secondary fragmentation products.

4.2. Siderophile elements

Both Co and Ni are strongly correlated with the “noble” siderophile element Ir among martian meteorites (Fig. 7). The ancient orthopyroxenite ALH84001 plots to the low-Ni side of the extrapolated correlations. In general, this sample appears to

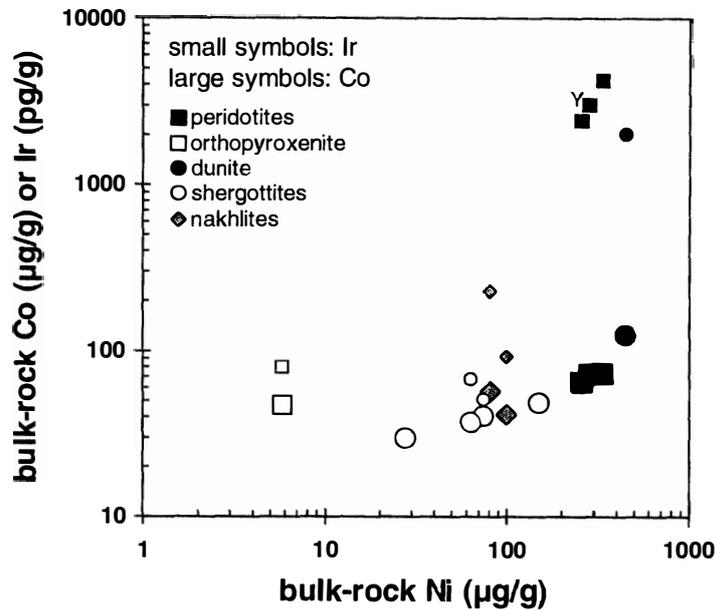


Fig. 7. Siderophile elements Ir and Co both show strong correlations with Ni among martian meteorites ("Y" is Y-793605).

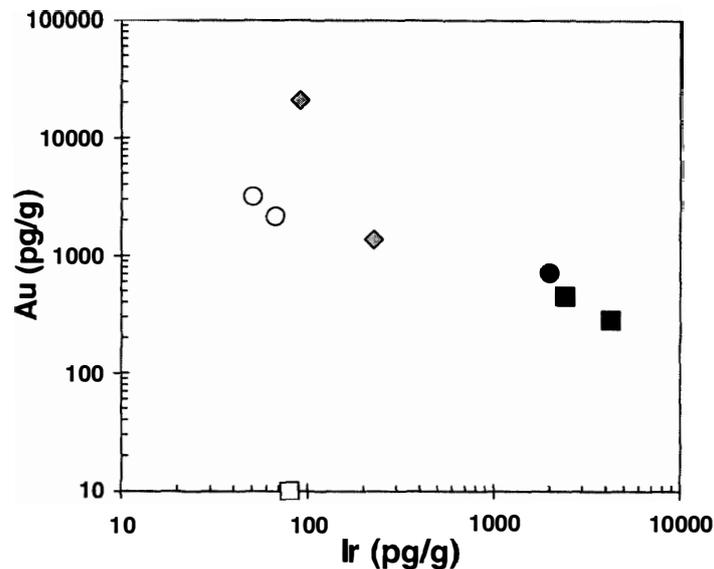


Fig. 8. Relationship between Au and Ir among martian meteorites: note the presence of the ALH84001 orthopyroxenite at the very bottom of the y axis, and the absence of the positive correlation that would be expected if Au were behaving as an Ir-like siderophile element (symbols as for Fig. 7).

have formed when the martian interior was in a reduced state compared to the modern Mars (WARREN and KALLEMEYN, 1996). Gold is usually considered a highly siderophile element among meteorites and lunar samples. However, if the aberrant ALH84001 is ignored, the correlation between Au and Ir among martian meteorites is, if anything, negative (Fig. 8). Most of the data shown in Fig. 8 are from the lit-

erature, and some of the Au values might be spuriously high—Au is notoriously susceptible to contamination, and INAA is poorly suited to determine Au at low concentrations (especially for Eu-rich samples). But clearly, the available data imply that among “young” martian meteorites Au is not ideally siderophile.

4.3. Origin of EET79001-A

The origin of the “A” lithology of EET79001 is enigmatic. It is in igneous contact with the EET79001-B lithology, and its bulk composition roughly corresponds to a mixture of EET79001-B with shergottitic peridotite material, and MCSWEEN and JAROSEWICH (1983) and WADHWA *et al.* (1994) interpret it as a product of magma mixing, or else (as a less favored hypothesis) assimilation of peridotitic matter by an EET79001-B type magma. However, MITTLEFEHLDT *et al.* (1997a) have argued instead that EET79001-A formed as an impact melt, contaminated with meteoritic Au, and containing clasts of EET79001-B and the EET79001-“X” peridotitic clots. MITTLEFEHLDT *et al.* (1997a) infer meteoritic Au contamination based on data obtained by INAA; other siderophile elements are not detectably enriched, they admit. Our own INAA data indicate a much smaller Au enrichment in EET79001-A relative to EET79001-B (Fig. 9).

We note some additional problematical aspects of the impact melt hypothesis. As discussed above, Au appears far from ideally siderophile in its behavior among “young” martian meteorites. The Au contamination interpretation is based on an assumption that the compositions of the pure, endogenously igneous components are known. The fit to the composition of EET79001-A as a two-component mix of EET79001-B plus any known shergottitic peridotite (SP) material is too poor to jus-

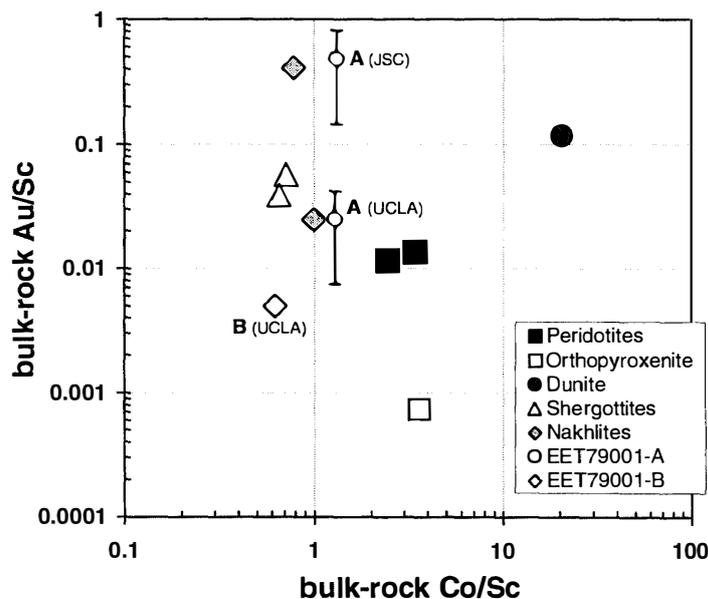


Fig. 9. Co/Sc vs. Au/Sc for martian meteorites, similar to the plot used by MITTLEFEHLDT *et al.* (1997a) to infer presence of meteoritic Au contamination in EET79001-A. Two-sigma error bars are shown for our EET79001-A result. The “JSC” EET79001-A data are from TREIMAN *et al.* (1994).

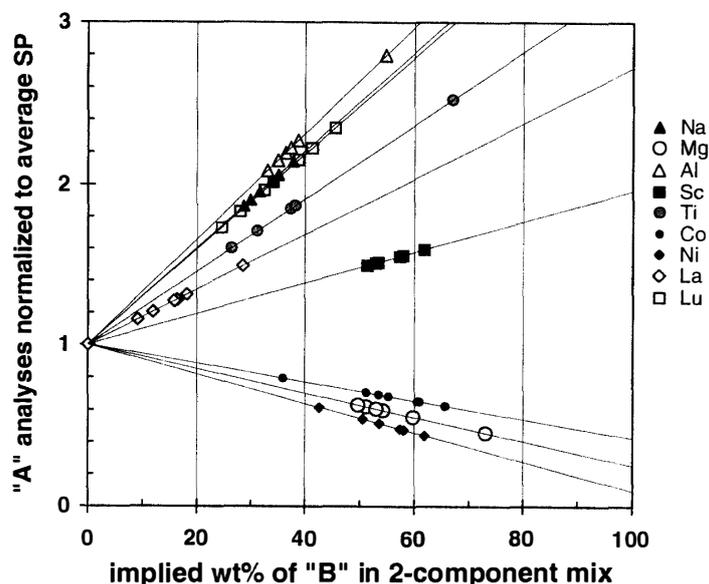


Fig. 10. Results from modeling individual EET79001-A analyses as mixtures of literature-averaged shergottitic peridotite and EET79001-B compositions (these averages are shown in Table 1). The individual EET79001-A analyses are from BURCHELE *et al.* (1983), SMITH *et al.* (1984), LAUL *et al.* (1986), JAROSEWICH (1990), TREIMAN *et al.* (1994), and Table 1.

tify such an assumption. As illustrated by Fig. 10, using the literature average SP as one component and the literature average for EET79001-B (see Table 1) as the other component, the mixing ratio that satisfies mafic elements such as Mg, Sc, Co and Ni is consistently about 55:45 (B:SP), whereas the plagiophile elements Na, Al, and Ga (not shown), and also the heaviest rare earth element Lu, consistently imply about 36:64; and the lightest REE, La, implies roughly 14:86. So the fit is actually quite rough. For comparison, using major and minor elements (oxides), WADHWA *et al.* (1994) fit the EET79001-A composition as a mixture of 56% EET79001-B plus 44% ALH77005. MITTFELDLT *et al.* (1997a) note that the fit is better using the ALH77005 “light” material (JAROSEWICH, 1990; TREIMAN *et al.*, 1994) as the SP component. However, by our calculations the implied mixing ratios are still seriously discrepant: average of about 57:43 (B:SP) for Mg, Sc, Co and Ni, versus ~41:59 for Na and Al, and 29:71 for La. For comparison, MITTFELDLT *et al.* (1997a), using the same two components but based on an unspecified suite of elements, found the overall best fit ratio to be 44:56.

The mixing model appears even rougher when V is considered, because in this case, the concentration in EET79001-A is not even intermediate between that in EET79001-B and the average SP composition. Figure 11 shows V plotted against Cr, a geochemically similar element that shows a rough correlation with V among different samples of EET79001-B and (much less tightly) the shergottitic peridotites. The V content of EET79001-B, especially in our relatively Cr-poor sample EET79001,399, is too low to account for the V content of EET79001-A by mixing with any plausible average composition for shergottitic peridotite. However, no V data are available for the ALH77005 “light” material, which has a relatively high Cr content (7.4–8.1

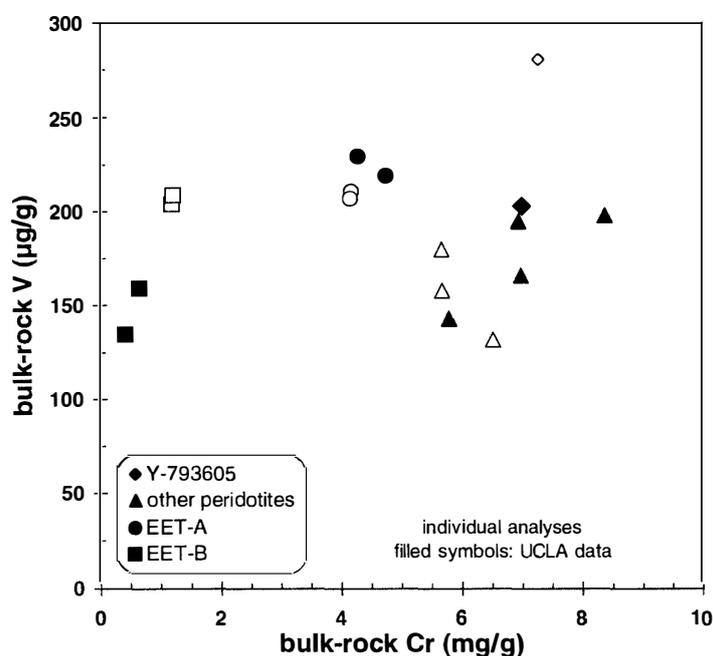


Fig. 11. Relationship between Cr and V among individual analyses of EET79001, Y-793605, and the other shergottitic peridotites (data sources as for Fig. 3, plus SMITH *et al.*, 1994). The average EET79001-A composition has a higher V concentration than both EET79001-B and any of nine shergottitic peridotite analyses, except that of EBHARA *et al.* (1997) for Y-793605. Variations shown are probably mainly due to real heterogeneities within the martian meteorites, not inter-laboratory bias. The smaller symbol (unfilled diamond) used for the EBHARA *et al.* (1997) Y-793605 point serves to remind that it was derived from a 123 mg chip, whereas our Y-793605 analysis (filled diamond) was derived from an aliquot of a 308 mg powder. The weighted mean Y-793605 composition, based on these two analyses, has $V=225 \mu\text{g/g}$.

mg/g: JAROSEWICH, 1990; TREIMAN *et al.*, 1994), and thus, based on the loose Cr-V correlation in Fig. 11, is conceivably rich enough in V to produce EET79001-A by mixing with EET79001-B.

Given the complexities of Au in martian meteorites (Figs. 8 and 9), the fit for the EET79001-A composition is probably even less reliable for Au than for well-determined, and geochemically better understood, elements such as Sc, V and La.

Lithology EET79001-A is a large mass, accounting for about 94% of this 8-kg meteorite (MEYER, 1996). Clasts within an individual impact melt are generally (although not always) of diverse provenance, and thus diverse petrologic nature (McCORMICK *et al.*, 1989). Yet EET79001-A, interpreted as an impact melt, would appear to contain only one clast of EET79001-B material, plus many clasts of the "X" peridotitic lithology (this tally ignores the late-formed lithology "C" material). Considering the extremely dissimilar natures of EET79001-B and EET79001-"X," formation of such a large mass of impact melt with clasts of these two materials only, and no clasts of petrologically distinct (or at least intermediate) lithologies, seems improbable.

In clast-rich impact melts, contacts between large clasts and the groundmass are

usually sharp, rather than gradational, because cool clasts efficiently chill hot surrounding melt, especially where the clast/melt ratio is high (SIMONDS *et al.*, 1976). Lithology EET79001-B is large (roughly 0.4 kg, as found, constituting one small end of EET79001) and, as noted above, the impact melt hypothesis implies that EET79001-A formed when impact melt of basaltic (B-like) composition mixed with a high proportion of peridotitic (lithology "X") clast material. Yet, "textural changes and modal proportions of pigeonite, augite and maskelynite are gradational between A and B over a distance of about one cm" (MCSWEEN, 1982). MCSWEEN and JAROSEWICH (1982) described the contact as gradational "in terms of modal variations" even over a distance of "several cm".

Another improbable aspect of the impact melt model is the low expectation of finding a "young" impact melt among just 12 samples (representing ~5 launch sites: EUGSTER and POLNAU, 1997) from Mars. WOODEN *et al.* reported (1982) that the Sr isotopic age of EET79001-A is 173 ± 10 ; EET79001-B is only marginally older, at 185 ± 25 Ma. CHEN and WASSERBURG (1986) found U-Th-Pb isotopic systematics for EETA79001-A to be "generally compatible with an age of 150–170 m.y."

As discussed above, estimates for the modern cratering rate on Mars range from roughly $1 \times$ to $4 \times$ the terrestrial rate (TREIMAN, 1995, has supplied a brief review). The proportion of the Earth's crust that has been impact melted over a similar interval can be estimated well enough to provide an interesting analogy. Numerical integration using models of impact melt genesis (MELOSH, 1989; GRIEVE and CINTALA, 1992) indicates that most planetary impact melt forms in a few extremely large events (WARREN, 1996). Thus, Chicxulub, with assumed diameter = 300 km (SHARPTON *et al.*, 1993), accounts for 97% of all the melt produced by the five known large impact craters younger than 200 Ma; the others being Popigai, Kara, Mastasin and Boltysh (GRIEVE and CINTALA, 1992). The extraordinary biospheric effects linked with Chicxulub imply it was probably the largest impact Earth has experienced in several hundred Ma. Thus, for purposes of extrapolation to Mars, the total volume of impact melt produced on Earth since 200 Ma can be approximated as the volume produced by Chicxulub, or at most 2–3 times that volume. The models of MELOSH (1989) and GRIEVE and CINTALA (1992) imply that Chicxulub produced roughly 2×10^5 km³ of impact melt; *i.e.*, only about 0.007% of the total volume of the Earth's crust. Assuming a similar crustal thickness for Mars, the volume of its crust is roughly $0.3 \times$ that of Earth's crust. After adjustment for this lower crustal volume, a possible $4 \times$ higher cratering rate on Mars (TREIMAN, 1995), and the effect of the $0.4 \times$ lower martian surface gravity (martian craters produce about $0.6 \times$ as much melt as terrestrial craters of equivalent diameter), the implied yield of post-200 Ma impact melt ($\sim 4 \times 10^5$ km³) is only about 0.06% of the volume of the martian crust. Conceivably, however, impact melting may enhance the statistical likelihood for derivation of martian meteoroids from a given area, by replacing mostly brecciated-weathered, and thus weak, near-surface rocks (WARREN, 1994), with strong, freshly crystallized rocks.

Our preferred interpretation is that EET79001-A is a product of magma mixing, roughly in the manner proposed by MCSWEEN and JAROSEWICH (1983) and WADHWA *et al.* (1994). However, we are not as confident as WADHWA *et al.* (1994) that the ultramafic component was mostly a molten magma, as opposed to a solid, or mostly

solid, mass of crystals. WADHWA *et al.* (1994) argued on the basis of heat balance calculations that a shergottitic magma could not assimilate enough solid peridotite to form EET79001-A. The thermal balance is a noteworthy constraint. However, as discussed above, the mixing models used to estimate the compositions and mixing proportions of the components in EET79001-A are only crudely accurate. Moreover, the heat balance calculations of WADHWA *et al.* (1994) treat the assimilation process as requiring complete equilibration of the peridotitic component into the combined magma. Actually, much of the peridotitic "X" component appears to have avoided equilibration. Olivines and orthopyroxenes occurring in EET79001-A as "megacrysts" (MCSWEEN and JAROSEWICH, 1983) or as components in ultramafic "clusters" of crystals (STEELE and SMITH, 1982) are strongly zoned; *e.g.*, for olivine, from Fo₈₁ to Fo₅₄ (STEELE and SMITH, 1982; MCSWEEN and JAROSEWICH, 1983). Texturally, the "X" component is grossly out of equilibrium with the groundmass—"X" mafic silicates have linear dimensions about 20× those of the groundmass counterparts (MCSWEEN and JAROSEWICH, 1983). TREIMAN (1993) even reports intact ultramafic "xenoliths" up to 1 cm across. A process of mechanical admixture of solids, with largely incomplete thermal/compositional equilibration, requires much less enthalpy than a process of ideal, total assimilation. Also, the admixed solids might easily have been concentrated, for example, by gravitational settling, or by flowage differentiation, into the marginal (next to EET79001-B) volume of magma that became EET79001-A.

5. Conclusions

The Y-793605 martian meteorite is remarkably similar to the ALH77005 and LEW88516 martian shergottitic peridotites. Almost certainly these three meteorites were all derived from the same small portion of a martian layered intrusion. Probably they originally crystallized in the lower-middle portion of the intrusion, and were still in very close proximity (separation of order 1–10 m) immediately prior to their launch off Mars. This trio of peridotites may have reached Earth via secondary fragmentation in the asteroid belt.

The complex EET79001-A lithology is only roughly approximated by models that mix the EET79001-B lithology with a component similar to the three shergottitic peridotites. The fit for V is particularly problematical. EET79001-A more likely formed by endogenous magma mixing than by the rare process of impact melting.

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