LEW88516 – 13.2 grams
Lherzolitic Shergottite

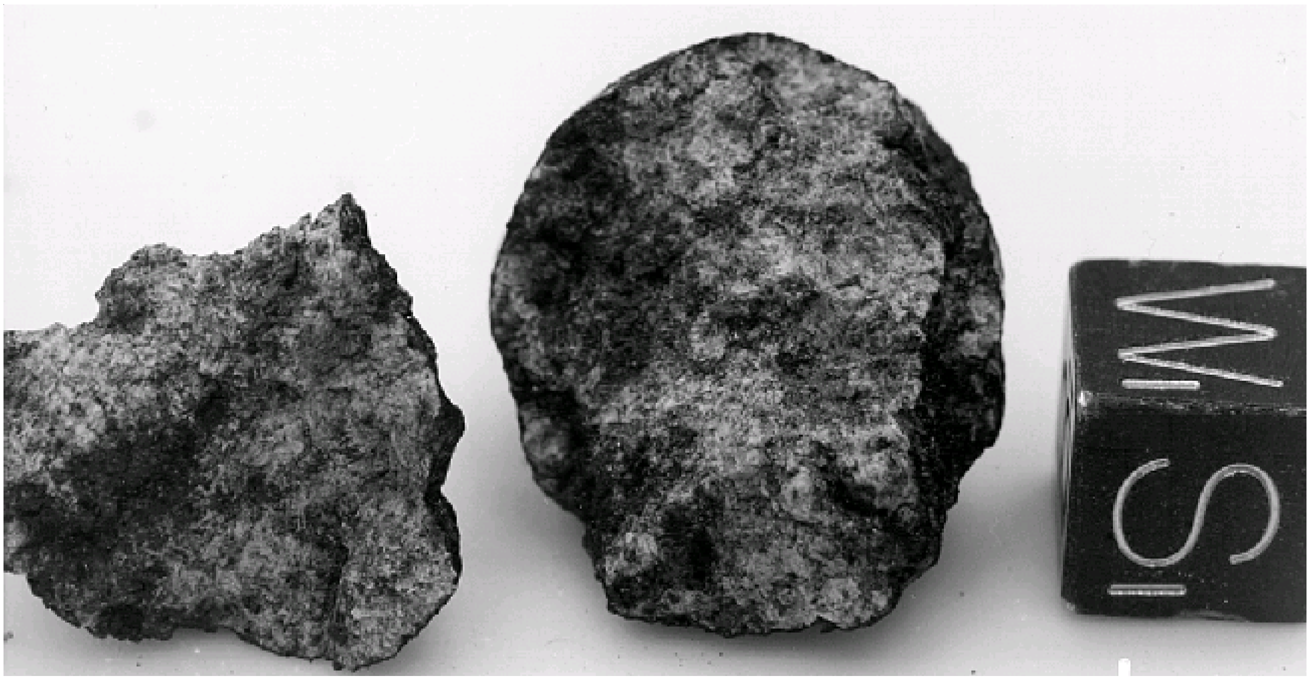

Figure 1. *Photograph of LEW88516 after first break for processing. Cube is 1 cm for scale. NASA # S91-37060*

Introduction
Lewis Cliff sample LEW88516 is petrologically similar to ALH77005 (Satterwhite and Mason 1991; Treiman *et al*. 1994) and Y793605 (Kojima *et al*. 1997). However, it is not paired, because it has a distinctly different terrestrial exposure age. Figure 1 shows LEW88516 as a small (2 cm), dark, rounded, meteorite with coarsely crystalline interior.

LEW88516 was a small nondescript meteorite that was not recognized as an achondrite until it was broken open Hence, it waited 2 years to be processed in numerical order. According to Satterwhite and Mason (1991), LEW88516 had a *"pitted and mostly shiny fusion crust over 80 % of the surface."* Preliminary examination of the thin section showed about 50 % olivine, 35 % pyroxene, 8 % interstitial maskelynite with about 5% brown glass. Grain size is about 2 - 3 mm.

Petrography
Harvey *et al.* (1993), Treiman *et al*. (1994), Gleason *et al*. (1997) and Mikouchi and Miyamoto (2000) have given detailed petrologic descriptions of LEW88516 and report that it is similar to ALHA77005 (figure 2). This meteorite has three distinct textural regions: 1) poikilitic crystalline, 2) interstitial crystalline (or non-poikilitic) and, 3) glassy to partially crystalline veinlets. Delaney (1992), Lindstrom *et al*. (1992) and Harvey and McSween (1992) have also reported petrological descriptions of LEW88516. Papike et al. (2009) compared LEW88516 with the roest of the shergottites.

In the poikilitic regions, mm-sized olivine crystals and 50 micron-sized chromite crystals are contained within, and completely surrounded by, pigeonite crystals with exsolution lamellae of augite. Maskelynite, whitlockite and sulfides are rare in the poikilitic regions.

The interstitial areas have a more typically basaltic texture with intergrown euhedral and subhedral olivine, pigeonite and chromite, with interstitial maskelynite, pigeonite, whitlockite, ilmenite and pyrrhotite.

The glass veinlets are the result of shock melting of the other lithologies (Harvey *et al.* 1993).

Melt inclusions in large olivine grains were studied by

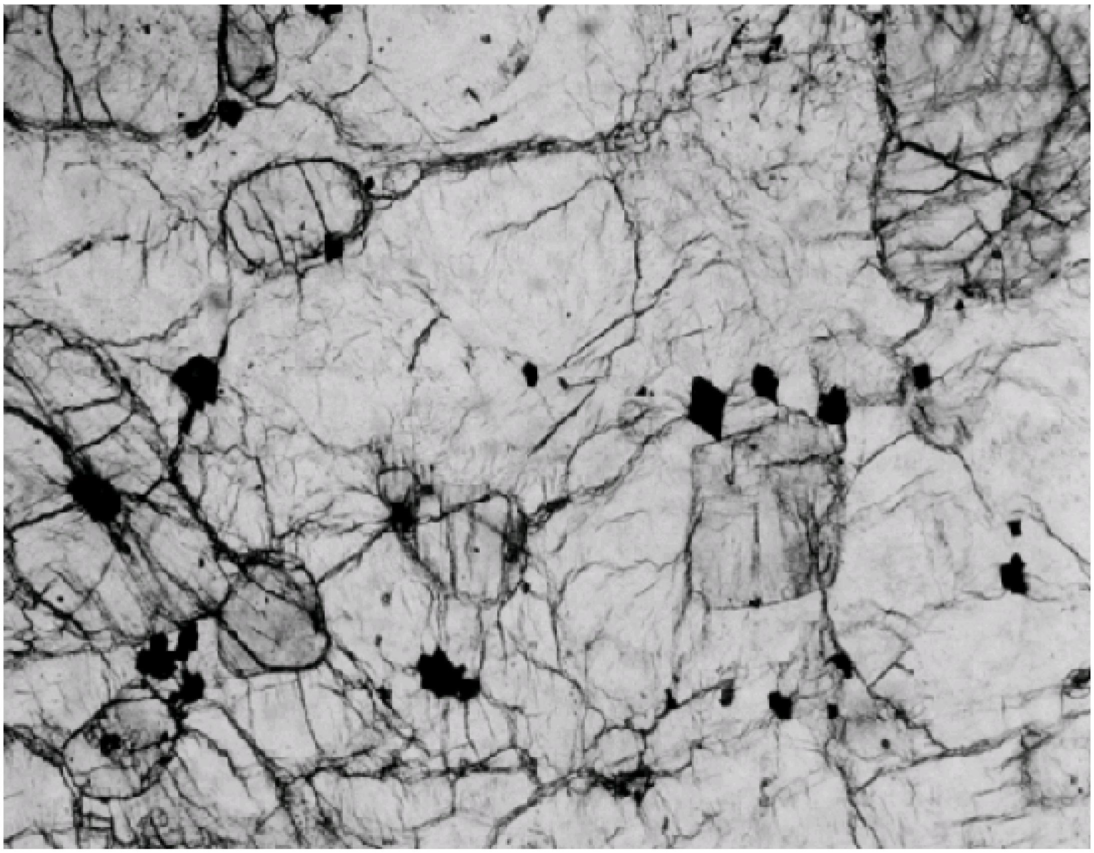

Figure 2. Photomicrograph of thin section LEW88516,6. Euhedral chromite and rounded olivine crystals poikilitically included in large orthopyroxene. Field of view is 2.2 mm.

Harvey *et al*. (1993) and used to calculate the composition of the parental melt - which was found to be similar to the calculated parental melt of other shergottites. Harvey *et al*. found that some melt inclusions contain two immiscible glasses (ratio 70:30), silica poor ~65% SiO_2 and extremely Si-rich (95%). Righter *et al.* (1998) determined the compositions of the melt inclusions, including the elements Rb, Ba, Mo and Ce (by ion probe).

Mineral Chemistry

***Olivine*:** Olivine is a major component of the poikilitic portion of LEW88516. It is compositionally zoned from Fo_{70} to Fo_{64}, averaging Fo_{67}. This is slightly more Fe-rich than the olivine in ALH77005. In both LEW88516 and ALH77005, the olivine has a distinct brown color apparently due to Fe^{+3} produced by "shock oxidation" (Ostertag *et al.* 1984).

***Pyroxene*:** Both low-Ca and high-Ca pyroxenes are present (figure 3). The large pyroxene oikiocrysts in the poikilitic portion are relatively homogeneous while the smaller pyroxenes in the non-poikilitic portion are zoned in composition. Harvey *et al*. (1993) have determined the REE and Ti, Al, Sc, Y, Zr, Cr and V contents of the different pyroxenes. Whereas the pyroxenes in LEW88516 are slightly more Fe rich, the trace element patterns are identical.

Mineralogical Mode

	Treiman *et al.* 1994	**Wadhwa *et al.* 1994**	**Gleason *et al.* 1997**
Olivine	45.9 vol. %	50-59	57
Pyroxene	37	35	22
Maskelynite	7	8-5	16
Phosphate	0.9	1.7	<1
Chromite	0.8	0.7-2	3
Ilmenite	0.2		
Pyrrhotite	0.3		<1
Glass	7.7		

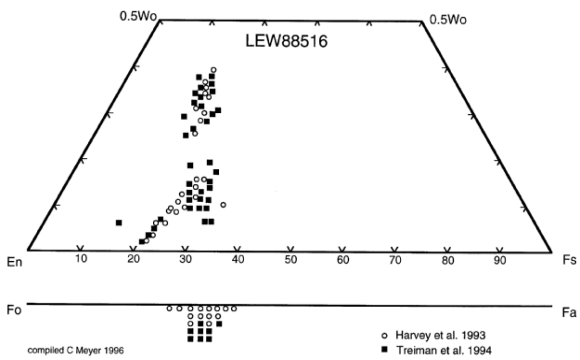

Figure 3. Composition diagram for pyroxene and olivine in LEW88516. Data are replotted from Harvey et al. (1993) and Treiman et al. (1994).

***Maskelynite*:** Maskelynite in LEW88516 has an average composition of An_{52} and a range from $An_{24\text{-}58}$ (Treiman *et al*. 1994) and is reported to contain small "bubbles".

***Chromite*:** Chromite is the most abundant accessory mineral in LEW88516. Chromite grains are commonly zoned or altered toward ulvöspinel compositions at their rims (Harvey *et al*. 1993; Gleason *et al.* 1997). Treiman *et al*. (1994) give the composition of 3 chromite grains and one grain that is a solid solution of titanomagnetite and chromite.

Ilmenite: Harvey *et al.* (1993), Treiman *et al.* (1994) and Gleason *et al.* (1997) give the composition of ilmenite (MgO = ~4-5 %).

***Kaersutite*:** Treiman (1998), Mikouchi and Miyamoto (2000) and Monkawa *et al.* (2001) have determined the composition of "kaersutitic" amphiboles found in melt inclusions in pigeonite within LEW88516.

***Phosphate:*:** Whitlockite occurs as a common accessory phase in the interstices of the non-poikilitic areas of LEW88516. Harvey *et al*. (1993) determined the REE content to be about 150X C1 chondrites. The REE pattern of the whitlockite is found to be very similar to that of the bulk rock, as was also the case for ALHA77005. Gleason *et al.* give the composition of whitlockite in LEW88516. Harvey *et al*. report apatite found in "melt inclusions" and give a composition.

***Sulfides*:** Dreibus *et al.* (1992), Harvey *et al*. (1993) and Treiman *et al*. (1994) reported pyrrhotite in LEW88516 and Dreibus *et al*. determined that it contained 1.8 % Ni.

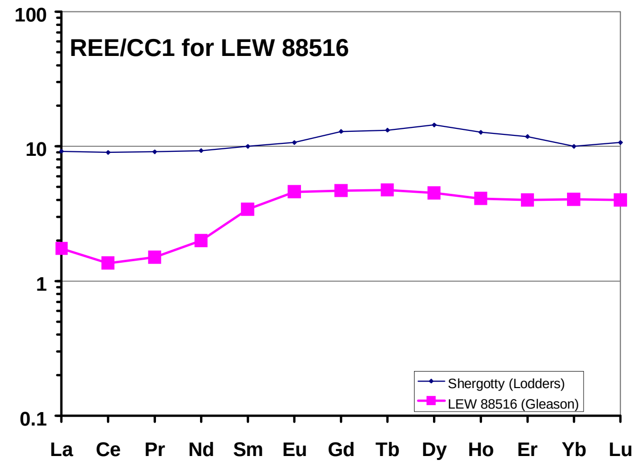

Figure 4. Normalized rare earth element diagram for LEW88516 compared with that of Shergotty. Data from Gleason et al. (1997).

Whole-rock Composition

Dreibus *et al*. (1992), Treiman *et al*. (1994) and Gleason *et al.* (1997) found that the composition of LEW88516 was almost identical to that of ALH77005 (figure 4). Ir was found to be low, in the range of the terrestrial upper mantle (Dreibus *et al*. 1992). *Analyses by Treiman et al. (1994) and by Warren and Kallemeyn (1996) indicate anomalous Ce.* Putchel et al. (2009) determined the PGE and Re

Radiogenic Isotopes

Borg *et al.* (1997, 2002) reported the crystallization age, as determined by Rb-Sr, to be 183 ± 710 m.y. with an initial $^{87}Sr/^{86}Sr$ of 0.71052 ± 4 (figure 5). Borg *et al*.

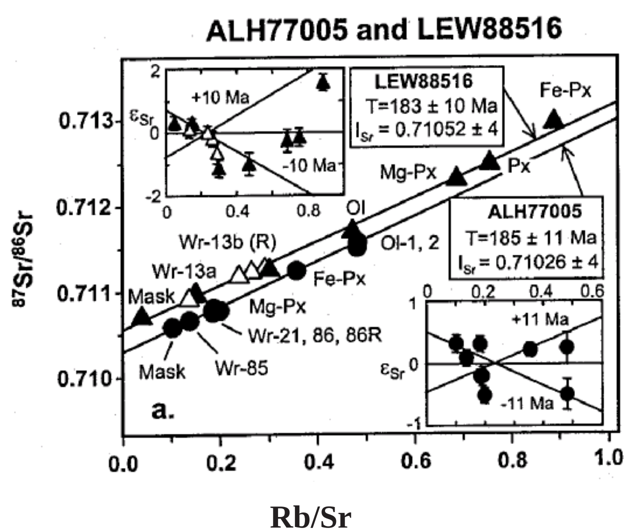

Figure 5. Rb-Sr isochron diagram for LEW88516 and for ALHA77005. This is figure 2 in Borg et al. (2002).

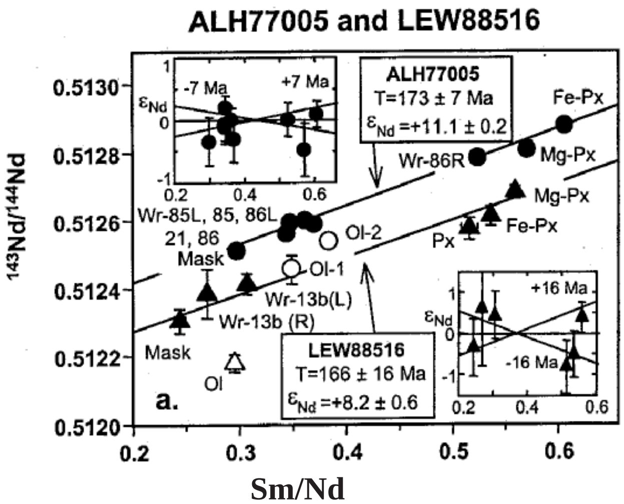

***Figure 6.** Sm-Nd isochron diagram for LEW88516 and for ALHA77005. This is figure 3 in Borg et al. (2002).*

(1998, 2002) reported an Sm-Nd isochron age of 166 ± 16 m.y. (figure 6). This agrees roughly with the U-Pb systematics as determined by Chen and Wasserburg (1993) who found that there was a lead-loss event ~ 170 m.y.

Cosmogenic Isotopes and Exposure Ages

Nishiizumi *et al*. (1992) and Jull *et al.* (1994) give a terrestrial exposure age of 21 ± 1 thousand years.

Treiman *et al*. (1994) used the ^{10}Be activity of 16.6 dpm/kg from Nishiizumi *et al*. (1992) to calculate an exposure age of LEW88516 of 3.0 m.y. Schnabel *et al*. (2001) also reported ^{10}Be, ^{26}Al and ^{53}Mn activity. Ott and Lohr (1992) and Becker and Pepin (1993) determined ^{3}He and ^{21}Ne contents and Eugster *et al*. (1996) calculated an exposure age for LEW88516 of 4.1 ± 0.4 m.y., concluding that LEW88516 was *"ejected from Mars simultaneously with the other lherzolitic shergottite ALH77005 (3.4 m.y.)."*

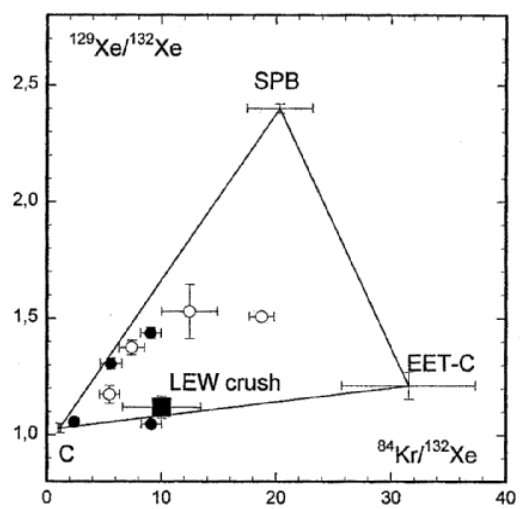

***Figure 7.** Krypton and Xenon isotopes for LEW88516 and other Martian meteorites as presented by Ott et al. (1996), M&PS **31**, 103. Data for Shergotty and Zagami are open circles and data from LEW88516 are filled symbols. SPB is "shergottite parent body".*

Other Isotopes

Ott and Lohr (1992), Bogard and Garrison (1993) and Becker and Pepin (1993) determined rare gas abundances in LEW88516. Becker and Pepin (1993) and Ott *et al.* (1996) determined that the noble gasses in a glass sample from LEW88516 were in the same ratio as those in EETA79001, but much less abundant (figure 7).

Clayton and Mayeda (1996) reported the oxygen isotope composition of LEW88516 verifying that it is Martian (see figure I-3).

The initial Sr and Nd isotope ratios differ slightly from those of ALH77005 (Borg *et al.* 1997, 1998, 2002). The isotopic composition of Os has been determined by Brandon *et al.* (1997).

Mohapatra et al. (2009) reported the rare gas isotopes. Becker and Pepin (1993) reported that they could not find heavy nitrogen to go along with the rare gasses.

Shock Features

Keller *et al.* (1992) and Treiman *et al.* (1994) found that the shock features in LEW88516 were very similar to those found in ALH77005. Stöffler (2000) estimated that LEW88516 was subjected to a shock pressure of ~ 45 GPa and post-shock temperature of ~600 deg. C.

Processing

This small (13.2g) achondrite has always been processed on a laminar flow bench in the Meteorite Processing Laboratory at JSC. Most of the allocations were done a few months after classification. Some of the allocations were interior, exterior or glass-rich chips (figure 8). Most allocations were from a homogenized powder prepared from 1.66 g of interior chips by Lindstrom and Mittlefehldt. Three potted butts have been used to produce 12 thin sections.

Table 1a. Chemical Composition of LEW88516.

reference	Dreibus92		Dreibus92		Treiman94		Treiman94		Treiman94		Warren96		Warren96		Warren96		Warren96	
weight					33 mg		39 mg		19 mg		glass-rich				glass-poor			
SiO2 %	45.5	(a)									47.06							
TiO2	0.42	(a)									0.4				0.26		.	
Al2O3	2.99	(a)									2.36				1.23			
FeO	19.49	(a)			19.5	(a)	19.3	(a)	23	(a)	18.27				16.47			
MnO	0.47	(a)													0.48			
CaO	4.06	(a)			4.3		4.4		3.7		4.925				4.757			
MgO	25.66	(a)									23.87				23.71			
Na2O	0.49	(a)			0.536		0.558		0.7		0.386				0.156			
K2O	0.024	(a)			0.031		0.03		0.033		0.289				0.182			
P2O5			0.39	(d)														
sum	99.1																	
Sc ppm	25.1	(a)			25.1	(a)	25.2	(a)	22.8	(a)	27.4	(a)			29.8	(a)		
V	180	(a)									196	(a)			198	(a)		
Cr	5672	(a)			5747	(a)	5816	(a)	5269	(a)	6900	(a)			8400	(a)		
Co	62.7	(a)			54.1	(c)	65.6	(a)	62.3	(c)	61.2	(a)			55.6	(a)		
Ni	250	(a)			280	(a)	300	(a)	300	(a)	226	(a)	244	(c)	229	(a)	230	(c)
Cu	<80	(a)																
Zn	70	(a)			47.1	(c)			54.7	(c)	62	(a)	52	(c)	66	(a)	50	(c)
Ga	8.4	(a)									7.6	(a)			5.8	(a)		
Ge													0.262	(c)			0.7	(c)
As	<0.15	(a)									<0.54	(a)			<0.47	(a)		
Se	<0.7	(a)			0.22	(c)			0.35	(c)	<0.73	(a)			<1.2	(a)		
Br	0.05	(a)																
Rb			0.83	(d)	0.174	(c)			0.199	(c)								
Sr			14.7	(d)	30	(a)	20	(a)										
Y			5.69	(d)														
Zr			17.2	(d)														
Nb			0.51	(d)														
Ag ppb					4.6	(c)			7.5	(c)								
Cd ppb					9.6	(c)			15.1	(c)			<0.072	(c)			0.07	(c)
In ppb					12.6	(c)			72.8	(c)								
Sb ppb					2.3	(c)			0.81	(c)								
Te ppb					<2	(c)			25	(c)								
I ppm	0.06	(a)																
Cs ppm			0.041	(d)	0.036	(a)	0.05	(a)	0.513	(c)								
Ba			4.93	(d)														
La	0.27	(a)	0.31	(d)	0.31	(a)	0.3	(a)	0.65	(a)	0.18	(a)			0.176	(a)		
Ce	0.94	(a)	0.87	(d)	1.4	(a)	1.9	(a)	2.4	(a)	<0.2	(a)			<0.4	(a)		
Pr																		
Nd			0.82	(d)														
Sm	0.39	(a)	0.47	(d)	0.416	(a)	0.42	(a)	0.82	(a)	0.315	(a)			0.241	(a)		
Eu	0.19	(a)	0.23	(d)	0.203	(a)	0.208	(a)	0.354	(a)	0.186	(a)			0.172	(a)		
Gd																		
Tb	0.14	(a)	0.16	(d)	0.17	(a)	0.16	(a)	0.3	(a)	0.14	(a)			0.116	(a)		
Dy	1.05	(a)	1.1	(d)														
Ho	0.19	(a)	0.24	(d)														
Er																		
Tm	0.11	(a)	0.089	(d)														
Yb	0.53	(a)	0.57	(d)	0.55	(a)	0.55	(a)	0.93	(a)	0.422	(a)			0.323	(a)		
Lu	0.078	(a)	0.083	(d)	0.076	(a)	0.076	(a)	0.14	(a)	0.071	(a)			0.059	(a)		
Hf	0.49	(a)	0.53	(d)	0.55	(a)	0.6	(a)	0.89	(a)	0.365	(a)			0.31	(a)		
Ta	0.027	(a)					30	(a)	40	(a)	<0.17	(a)			<0.17	(a)		
W ppb	<250	(a)																
Re ppb													0.071	(c)			0.064	(c)
Os ppb													1.79	(c)			2.56	(c)
Ir ppb	3.4	(a)			2.1	(a)	2	(a)			6.7	(a)	1.58	(c)	<5		2.32	(c)
Au ppb	0.7	(a)			0.42	(c)			0.61	(c)			0.34	(c)			0.21	(c)
Tl ppb					4.9	(c)			4.2	(c)								
Bi ppb					1.5	(c)			3.2	(c)								
Th ppm	<0.06	(a)	0.04	(d)					0.08	(a)	<0.1	(a)			<0.13	(a)		
U ppm	0.013	(a)	0.011	(d)	0.012	(c)			0.0243	(c)								

technique: (a) INAA, (b) IDMS, (c) RNAA, (d) spark source mass spec.

Table 1b. Composition of LEW88516 (continued).

reference	Lodders 98	Warren 96		Warren 96		Gleason 97		Gleason 97		Brandon 2000		Borg 2001	
weight	*average*	*powder*				*147 mg*		*147 mg.*		*103.8 mg.*		*25 mg.*	
SiO2	46												
TiO2	0.39	0.32				0.36	(a)	0.45	(a)				
Al2O3	3.31	2.93				3.45	(a)	3.86	(a)				
FeO	19	18.91				20.9	(a)	20.3	(a)				
MnO	0.49	0.48				0.51	(a)	0.51	(a)				
CaO	4.2	4.114				4.25	(a)	4.54	(a)				
MgO	25	25.5				23.7	(a)	24.9	(a)				
Na2O	0.56	0.516				0.588	(a)	0.595	(a)				
K2O	0.029	0.301				0.028	(a)	0.028	(a)				
P2O5	0.39												
sum													
Sc ppm	25	25.2	(a)			26.7	(a)	26.5	(a)				
V	170	143	(a)			171	(a)	178	(a)				
Cr	5880	5800	(a)			6295	(a)	6568	(a)				
Co	65	66.7	(a)			66.5	(a)	64.1	(a)				
Ni	280	245	(a)	254	(c)	315	(a)	276	(a)				
Cu													
Zn	60	69	(a)	54	(c)	62.1	(a)	60.6	(a)				
Ga	9.2	8.7	(a)			9.1	(a)	10.4	(a)				
Ge	0.6			0.6	(c)								
As	<0.93	<0.93	(a)										
Se	0.34	<0.64	(a)			0.35	(a)	0.44	(a)				
Br	0.05												
Rb	1.1					1.41	(a)	0.97	(a)			0.657	(a)
Sr	17					14.3	(a)	17.7	(a)			12.9	(a)
Y	5.7												
Zr	13					12.4	(a)	9.6	(a)				
Nb	0.51												
Mo													
Pd ppb													
Ag ppb	6.1												
Cd ppb	12.4			<0.08									
In ppb	12.6 or 72.8												
Sb ppb	1.6												
Te ppb	25												
I ppm	0.06												
Cs ppm	0.055					0.079	(a)	0.06	(a)				
Ba	4.9												
La	0.33	0.3	(a)			0.41	(a)	0.41	(a)				
Ce	1.26	2.1	(a)			0.8	(a)	0.82	(a)				
Pr													
Nd	0.82											0.447	(b)
Sm	0.44	0.4	(a)			0.474	(a)	0.502	(a)			0.267	(b)
Eu	0.22	0.221	(a)			0.242	(a)	0.256	(a)				
Gd													
Tb	0.16	0.14	(a)			0.167	(a)	0.172	(a)				
Dy	1.08												
Ho	0.23					0.247	(a)	0.23	(a)				
Er													
Tm	0.1												
Yb	0.57	0.5	(a)			0.658	(a)	0.656	(a)				
Lu	0.083	0.079	(a)			0.091	(a)	0.097	(a)				
Hf	0.52	0.43	(a)			0.514	(a)	0.548	(a)				
Ta	0.035	<0.22	(a)					0.041	(a)				
W ppb	140					0.11	(a)	0.17	(a)				
Re ppb	<0.09			0.09	(c)					0.0222	(b)		
Os ppb	3.3			3.3	(c)					0.905	(b)		
Ir ppb	3			3.1	(c)	3.6	(a)	3.8	(a)				
Au ppb	0.53			0.39	(c)								
Tl ppb	4.6												
Bi ppb	2.4												
Th ppm	0.037	<0.09	(a)					0.044	(a)				
U ppm	0.014												

technique: (a) INAA, (b) IDMS, (c) RNAA

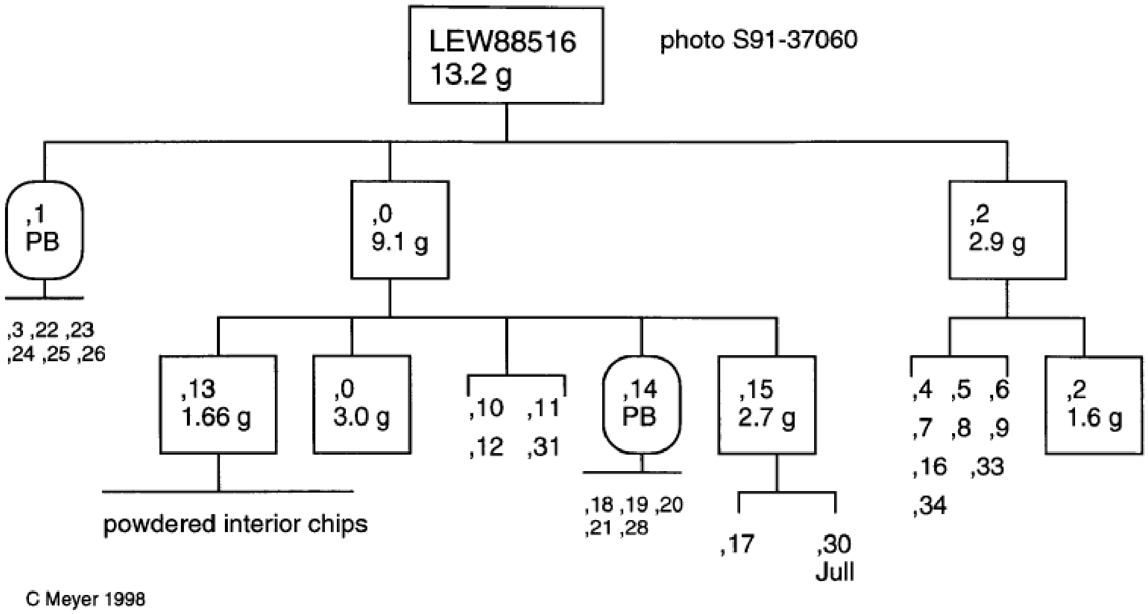

Figure 8. *Genealogy diagram for LEW88516 for samples allocated up to 1997.*

LEW88516 is listed as a "restricted" sample by the MWG (Score and Lindstrom 1993, page 5), because of its small size.

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