

## V. Shergotty

basalt, 5 kg  
*seen to fall*

### **Introduction**

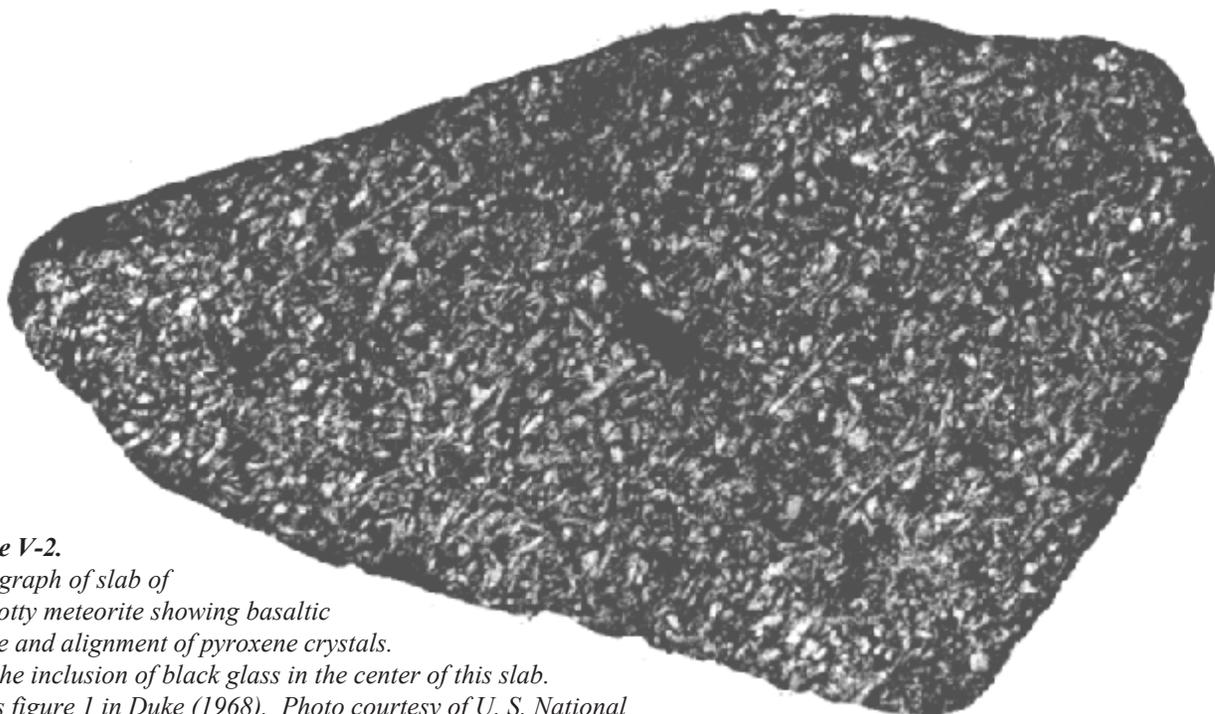
The Shergotty achondrite fell on August 25, 1865 at 9:00 a.m. near a town called Shergahti in Bihar State, India after detonations were heard (Graham *et al.* 1985). Duke (1968) refers to several stones with fusion crusts, *but this has not been confirmed*. The main mass is at the Museum of the Geological Survey in Calcutta, India (figure V-1). In 1984, an international consortium was organized by J. C. Laul to study ~30 grams of Shergotty in detail (Laul 1986a, b).

Shergottites (Shergotty, Zagami, EETA79001B, QUE94201, Los Angeles) are texturally and mineralogically similar to terrestrial diabases (although all of the plagioclase has been shocked to maskelynite), but quite distinct petrologically and chemically from the rest of the basaltic achondrites (Stolper *et al.* 1979). Stolper and McSween (1979) and others have noted that Shergotty crystallized under relatively oxidizing conditions.

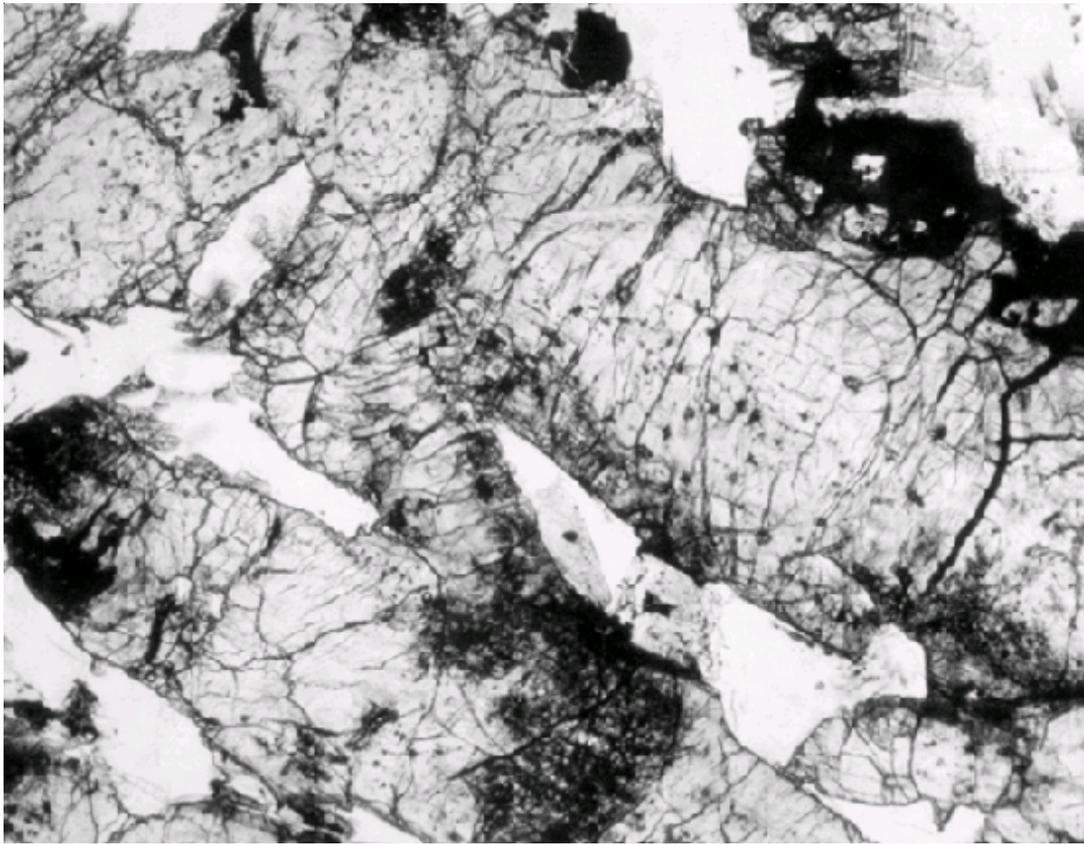
The Shergotty meteorite has been severely shocked and is considered the “*type locality*” for maskelynite (dense plagioclase glass). In fact, it has proven to be very difficult to date the original crystallization event of



**Figure V-1.** Photograph of Shergotty meteorite showing fusion crust and broken surfaces. Two saw cuts are visible. Sample is about 25 cm across. Photo kindly provided by Prof. N. Bhandari, Director, Physical Research Laboratory, Ahmedabad, India.



**Figure V-2.** Photograph of slab of Shergotty meteorite showing basaltic texture and alignment of pyroxene crystals. Note the inclusion of black glass in the center of this slab. This is figure 1 in Duke (1968). Photo courtesy of U. S. National Museum, negative # M-1426. Sample # USNM321. Slab is about 6 cm across.



**Figure V-3.** Photomicrograph of thin section of Shergotty meteorite showing large zoned, clinopyroxene crystals intergrown with white plagioclase (maskelynite) laths. This section loaned by G. McKay. Field of view is 2.2 mm.

Shergotty, perhaps because of the rather severe shock history that the sample has experienced since it originally crystallized (see *El Goresy et al. 1998; Malavergne et al. 2001*). In addition, small areas of Shergotty have been shock-melted.

**Petrography**

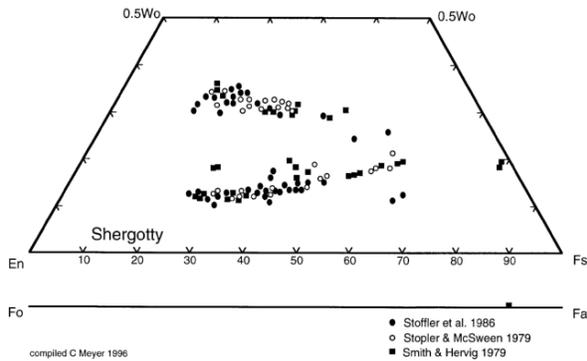
The mineralogy and petrology of Shergotty have been comprehensively studied by many investigators (e.g. Tschermak 1872; Binns 1967; Duke 1968; Smith and Hervig 1979; Stolper and McSween 1979; Nakamura *et al.* 1982; Jagoutz and Wänke 1986; Stöffler *et al.*

1986; Lundberg *et al.* 1988; McSween and Treiman 1998 and others).

Shergotty consists of dull gray-green pyroxene prisms up to 1 cm long with colorless lath-like and interstitial vitreous maskelynite which has replaced the feldspar (Duke 1968). Shergotty exhibits a foliated texture produced by preferential orientation of pyroxene prisms and maskelynite grains (Duke 1968; Stolper and McSween 1979)(figure V-2). The texture was described as ophitic by Michel (1912), but the rather euhedral pyroxene does not enclose feldspar (Duke 1968). The average grain size for Shergotty is only

**Mineralogical Mode**

	Stolper & McSween 1979		Duke 1968	Smith & Hervig 1979	Stöffler <i>et al.</i> 1986
	<i>mode</i>	<i>mode</i>	<i>norm</i>	<i>mode</i>	<i>mode</i>
Pyroxene	70.5	69.1	68.9	70	67
Plagioclase	23.9	22.7	24.0	20	24
Mesostasis	2.8	5.2		3	3
Magnetite	2.0	2.5	2.3	2	2
Ilmenite	0.5	0.3	1.8	0.5	0.2
Pyrrhotite	0.3	0.2	--		0.4
Phosphate	tr	tr	1.3	1	2
silica					0.5



**Figure V-4.** Pyroxene and olivine composition diagram for Shergotty meteorite. Data from Stöffler *et al.* (1986), Stolper and McSween (1979) and Smith and Hervig (1979).

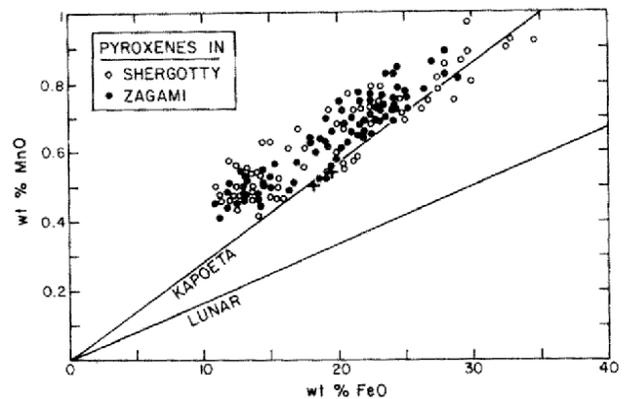
about 0.46 mm (figure V-3). Lentz and McSween (1999) find that there are two “humps” in the grain size distribution for Shergotty.

In thin section, pyroxene prisms vary in color from light brown in the cores to yellow brown at the rims, reflecting a marked enrichment of iron at the rims (Duke 1968). Maskelynite is transparent, colorless, conchoidally-fractured, isotropic and is a pseudomorph after plagioclase (see below). Based on the texture, plagioclase crystallized late in the sequence of crystallization (Stolper and McSween 1979; Treiman 1985a).

Melt inclusions in pyroxene are an important assemblage in Shergotty (Nyquist *et al.* 1979; Treiman 1985a). They represent trapped magmatic liquid and may allow a determination of the age of entrapment during crystallization (see below).

The coexistence of fayalite, Ti-magnetite and a silica glass indicates late-stage crystallization under relatively high oxygen fugacity (Smith and Hervig 1979). Aramovich *et al.* (2002) have studied fine-grained symplectite intergrowths in Shergotty and argue that they are the result of “breakdown” of metastable pyroxferroite and ferrosilite.

Shergotty should be examined for the presence of large shock-melted “glass pockets” similar to those found in Zagami and EETA79001 (figure V-2). In fact, Stöffler *et al.* (1986) refer to substantial amounts of “localized *in-situ melting*” confined to grain boundaries between pyroxene and opaque phases.



**Figure V-5.** Variation between MnO and FeO in pyroxenes in Shergotty and Zagami meteorites. This is figure 5 of Stolper and McSween 1979, *GCA* 43, 1480.

## Mineral Chemistry

**Pyroxene:** Pyroxene in the Shergotty meteorite consists of separate grains of pigeonite and sub-calcic augite, both with a homogeneous interior and a strongly zoned, Fe-rich rim (figure V-4). Smith and Hervig (1979), Stöffler *et al.* (1986) and Lundberg *et al.* (1988) have studied pyroxene zoning - both major and trace elements. There are two trends, Ca-rich from  $En_{48}Fs_{19}Wo_{33}$  to  $En_{25}Fs_{47}Wo_{28}$ , and Ca-poor from  $En_{61}Fs_{26}Wo_{13}$  to  $En_{21}Fs_{61}Wo_{18}$ . Mn increases along with Fe (figure V-5), and Smith and Hervig and Stolper and McSween (1979), found that the trend is towards an intercept of MnO near 0.2 % for low Fe. The preservation of extreme chemical zoning in pyroxenes indicates rapid cooling (Mikouchi *et al.* 1999). Wadhwa *et al.* (1994) studied the trace element contents of pyroxenes in Shergotty. Lentz *et al.* (2002) have also studied trace elements in pyroxenes and found that while Be increases, Li and B generally decrease in concentration from core to rim.

Müller (1993) studied “microstructures” in Shergotty clinopyroxene. Fine scale exsolution also argues for rapid crystallization in a lava flow or sill about 40-60 meters thick.

**“Pyroxferroite”:** Smith and Hervig (1979) reported minute grains of pyroxferroite included in maskelynite. However, Aramovich *et al.* (2002) argue against this finding.

**Maskelynite:** Shergotty is the type-specimen for maskelynite (Tschermak, 1872), a plagioclase glass formed by high shock pressures estimated at ~300 Kbars (Smith and Hervig 1979) or 29 GPa (Stöffler *et*

*al.* 1986). Binns (1967) found that the maskelynite in Shergotty lacks any crystal structure, as evidenced by isotropism and absence of diffraction lines in long-exposure X-ray powder photographs. Duke (1968) noted that the refractive indices and specific gravities of maskelynite grains are variable, and suggested that individual crystals are zoned. Easton and Elliot (1977) reported the composition of “feldspar/glass” from Shergotty as  $An_{51}Ab_{46}Or_2$ . Stolper *et al.* (1979) determined that individual maskelynite grains are zoned from  $An_{57}Ab_{42}Or_1$  to  $An_{43}Ab_{53}Or_4$ . Mikouchi *et al.* (1999) carefully studied zoning trends that are preserved in maskelynite in Shergotty (and other shergottites). Using the TEM, Chen and El Goresy (2000) and Malavergne *et al.* (2001) find that some of the maskelynite in Shergotty is truly amorphous plagioclase glass (indicating higher shock pressure). Lentz *et al.* (2002) determined Li, Be and B in plagioclase

***K-rich inclusions:*** The pyroxenes in Shergotty contain K (and Rb) rich inclusions (Nyquist *et al.* 1979). It is these inclusions that apparently define the Rb/Sr isochron.

***Phosphates:*** Most of the trace elements in Shergotty are located in the phosphates. Fuchs (1969) and Stolper and McSween (1979) give analyses of whitlockite (merrillite?) in Shergotty (see appendix VII). Fuchs (1969) first noted that “whitlockite” from Shergotty had distinctively high iron content. Jagoutz and Wänke (1986) give the composition of apatite and whitlockite. Smith and Hervig (1979) reported merrillite (?) in glass veins. Lundberg *et al.* (1988) analyzed both whitlockite and apatite for REE by ion microprobe. Wadhwa *et al.* (1994) compare whitlockites in the shergottites. In 1996, Dreibus and Wänke performed detailed leaching experiments on the phosphates.

***Magnetite:*** Tschermak (1872) was the first to recognize primary magnetite in Shergotty. This important observation, overlooked for many years, indicates a relatively high degree of oxidation at the time of crystallization. Stolper and McSween (1979) give an analysis of titanomagnetite.

***Baddeleyite:*** Smith and Hervig (1979) reported rare, small (~1 micron) grains of baddeleyite. Lundberg *et al.* (1988) found that baddeleyite had a flat REE pattern.

***Hercynite spinel:*** Treiman (1985) reported Fe, Al-rich spinel in magmatic inclusions in pyroxene.

***Amphibole:*** Treiman (1984, 1985) reported pleochroic amphibole in the magmatic inclusions in pyroxene. Amphibole has been analyzed for D/H ratio by Watson *et al.* (1994).

***Sulfide:*** The sulfide in Shergotty was recognized to be pyrrhotite by Tschermak (1872). Smith and Hervig (1979) describe it as “homogeneous with molar Fe:S of 0.94, and 0.12 wt % Ni, 0.03 Cu.” It is found in the rims of the pyroxene and in the mesostasis. Rochette *et al.* (2001) have found that ~0.5 % pyrrhotite best explains the magnetic properties of Shergotty, but they warn that shock-heating events easily reset remanent magnetism recorded in this phase.

***Silica:*** Duke (1968) reported silica (cristobalite?), but could not find x-ray lines for coesite. Stöffler *et al.* (1986) reported a large grain (~200 microns) of  $\alpha$ -quartz adjacent to maskelynite and one grain of possible stishovite (?). El Goresy *et al.* (1996, 1997, 1998, 2000), Chen and El Goresy (2000) and Sharp *et al.* (1999) found that “silica grains in Shergotty consist of two phases: (i) a dense amorphous silica glass, and (ii) a post-stishovite polymorph of  $SiO_2$ ”. Malavergne *et al.* (2001) report beta-cristobalite (see section on Shock Effects).

***Fayalite:*** Smith and Hervig (1979) found that fayalite ( $Fe_{10}$ ) was present in the mesostasis adjacent to magnetite-ilmenite grains.

***Majorite:*** Malavergne *et al.* (2001), identified four small grains (600 Å) of Ca-rich majorite (cubic garnet structure) embedded within an Si-Al-rich amorphous phase. It has the same composition as the pyroxene in which it is located.

### **Whole-rock Composition**

The major element composition of Shergotty has been determined by Tschermak (1872), Duke (1968), McCarthy *et al.* (1974), Dreibus *et al.* (1982) and Barret *et al.* (2001). The Shergotty Consortium (Laul *et al.* 1986) obtained additional chemical data on Shergotty (table V-1). The REE data are compared in figure V-6. Laul *et al.* (1986) noted a slight difference in the REE abundance from fragments B and C from opposite sides of the main mass, possibly indicating some heterogeneity in the sample.

Jovanovic and Reed (1987) reported 470 ppb Hg (probably museum contamination).

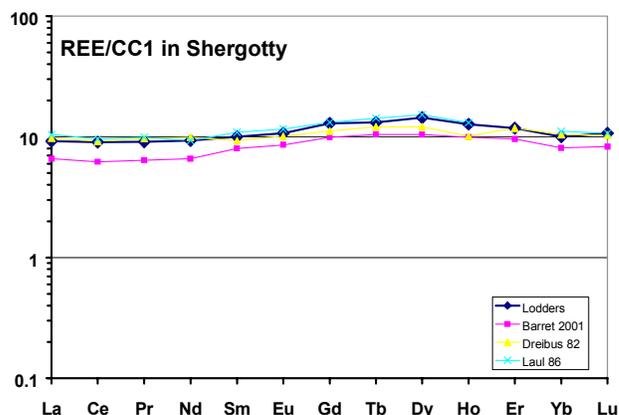
Yang and Epstein (1985) reported 180 ppm H<sub>2</sub>O in Shergotty. Karlsson *et al.* (1992) reported 640 ppm H<sub>2</sub>O, but recognized that some of this may be terrestrial (see section on Other Isotopes). Leshin *et al.* (1996) found (0.041 wt% H<sub>2</sub>O). Gooding *et al.* (1990) determined the thermal release pattern for several volatile species (H evolved as HCl!).

Stolper (1979) noted the remarkable similarity of the compositions of Shergotty and Zagami with terrestrial basalts for a wide range of elements (see figure I-8). Dreibus *et al.* (1992) noted that Shergotty had much less Ir than the other Martian meteorites and/or terrestrial “upper mantle.”

*Note: The values for the composition of Shergotty reported by Schmitt et al. (1972) are so far off that Smith and Steele (1979) asked if they analyzed the wrong sample! Also, the values given for Shergotty in the book on Basaltic Volcanism (Lofgren and others, 1981) do not seem to be consistent with literature values.*

### Radiogenic Isotopes

The original crystallization age of Shergotty has proven to be most difficult to determine, partially because of the shock history and the analytical difficulties associated with dating young samples with low abundances of radiogenic trace elements (Nyquist *et al.* 2001). Geiss and Hess (1958) originally determined a K/Ar age of 560 Ma (+60-150), and suggested that the Rb/Sr technique be used (page 233). Twenty one years later, Nyquist *et al.* (1979) finally determined an internal Rb/Sr isochron for Shergotty of 165 ± 11 Ma with high I<sub>Sr</sub> = 0.72260 ± 0.00012 (figure V-7) (λ<sub>Rb</sub> = 1.39 × 10<sup>-11</sup> year<sup>-1</sup>). However, Bogard *et al.* (1979) attempted to determine the <sup>39</sup>Ar/<sup>40</sup>Ar age and found that



**Figure V-6.** Normalized rare-earth-element (REE) patterns for Shergotty as determined by various teams (Table V-1).

the maskelynite gave a plateau age of 254 ± 10 Ma (figure V-8). Bogard and Garrison (1998) have carefully re-corrected the Ar data and calculate an age of 165 Ma.

Jagoutz and Wänke (1986) repeated the work of Nyquist *et al.* and reported a Rb/Sr age of 167 Ma using maskelynite and mesostasis with high I<sub>Sr</sub> = 0.72263 ± 0.00005. They also reported two Sm-Nd ages (147 ± 20 Ma for leaches of the “whole rock” and 360 ± 16 Ma for the pyroxene separates and leaches)(figure V-9). Shih *et al.* (1982) were unable to use the Sm-Nd system to determine a precise crystallization age for Shergotty.

By leaching “whole rock” samples of Shergotty, Chen and Wasserburg (1986a) obtained a U-Pb “isochron” of 200 ± 4 Ma (figure V-10) and a Th-Pb “isochron” of 205 ± 8 Ma (figure V-11). These leach experiments probably attacked the phosphates in the sample (see section on Experiments below). By leaching the more refractory “pyroxene” separates, Chen and Wasserburg obtained “ages” 600 ± 20 Ma for U-Pb and 437 ± 36

### Halogens (and S) (in ppm)

	F	Cl	Br	I	S
Reed and Jovanovic (1969)	56.2				
Allen and Clark (1977)	58				
Gibson (1985)					360, 2170
Dreibus <i>et al.</i> (1983)	41.6	108			1330
Laul <i>et al.</i> (1986)				1579	
Burgess (1989)					1930
Dreibus and Wanke (1987)		108	.89	.036	
Sawyer <i>et al.</i> (2000)	187	22.1			
	178	21.5			

Table V-1. Chemical composition of Shergotty.

	Treiman 86	Dreibus 82	McCarthy 74	Jerome 70	Philpotts70	Tscher. 1872	Duke 1968	Smith 84	Shih 82	Ma 81	Warren 87
<i>weight</i>	<i>0.1-0.2 g</i>		<i>1 g</i>	<i>1.065 g</i>							<i>(Irving)</i>
SiO <sub>2</sub> %		51.36	50.36 (f)	51.48 (a)		50.21 (e)	50.1 (e)				
TiO <sub>2</sub>		0.87	0.85 (f)	0.81 (a)			0.92 (e)				
Al <sub>2</sub> O <sub>3</sub>		7.06	7.03 (f)	5.75 (a)		5.9 (e)	6.68 (e)				6.42
Fe <sub>2</sub> O <sub>3</sub>							1.49 (e)				
FeO		19.41	19.34 (f)	19.8 (a)		21.85 (e)	18.66 (e)				18.93
MnO		0.52	0.54 (f)	0.49 (a)			0.5 (e)				0.515
CaO		10	9.58 (f)	10.25 (a)		10.41 (e)	10.03 (e)				8.81
MgO		9.28	9.27 (f)	9.35 (a)		10 (e)	9.4 (e)				9.78
Na <sub>2</sub> O		1.29	n.d.	1.31 (a)		1.28 (e)	1.28 (e)				1.34
K <sub>2</sub> O		0.164	0.18 (f)	0.13 (a)	0.18 (d)	0.51 (e)	0.16 (e)				0.178
P <sub>2</sub> O <sub>3</sub>		0.8	0.47 (f)				0.71 (e)				
<b>sum</b>		<b>100.754</b>	<b>97.62</b>	<b>99.37</b>		<b>100.16</b>	<b>99.93</b>				
Li ppm		5.6							4.1 (d)		
C		620									
F		41.6									
S		1330									
Cl		108									
Sc		58.9			<b>Jerome 70</b>						
V				48 (b)	50.3 (c)		72 (b)	52		53 (c)	53
Cr				380 (b)			340 (b)				290
Co		1389	2100 (f)	1500 (b)	1400 (c)	<b>Laul 72</b>	1150 (b)				1330
Ni	55 (g)	83		37 (b)	39.5 (c)	63 (g)	42 (b)	38 (g)		35 (c)	39
Cu		26		81 (b)			100 (b)	56		56 (c)	80
Zn	68.3 (g)	83		11 (b)		11.9 (g)		54			54
Ga		14.7				76 (g)		76 (g)			16.7
Ge	0.69 (g)					13.9 (g)		15 (g)			
As		0.025						6.03 (g)			
Se	0.37 (g)	0.41				0.242 (g)		0.47 (g)			
Br	1.06 (g)	0.891 (j)				1.07 (g)					
Rb	9.5 (g)	6.84			0.13 (d)	6.1 (g)		5.7	6.22 (d)		
Sr		51		35 (b)	50.7 (d)		8 (b)		51 (d)		
Y				<10 (b)			19 (b)				
Zr							41 (b)				
Nb							22 (b)				
Mo											
Pd ppb	1.7 (g)										
Ag ppb	16.9 (g)					263 (g)		110 (g)			
Cd ppb	12.9 (g)					44 (g)		340 (g)			
In ppb	26.5 (g)					31.3 (g)		23 (g)			
Sb ppb	1.7 (g)	<5						27 (g)			
Te ppb	2.5 (g)							3.2 (g)			
I ppm		0.036 (j)									
Cs ppm	0.529 (g)	0.405			<b>Schnetz. 69</b>	0.38 (g)		0.44 (g)			
Ba		35.5		40 (b)	32 (d)		6 (b)		29.4 (d)		
La		2.29		1.93 (c)					1.5 (d)	2.18 (c)	1.99
Ce		5.54			5.89 (d)				3.51 (d)		
Pr		0.86									
Nd		4.5			4.96 (d)				2.6 (d)		
Sm		1.37		1.37 (c)	1.89 (d)				1.01 (d)	1.36 (c)	1.27
Eu		0.564		0.55 (c)	0.643 (d)				0.43 (d)	0.53 (c)	0.56
Gd		2.2			2.8 (d)				1.64 (d)		
Tb		0.44								0.36 (c)	
Dy		2.94			3.38 (d)				2.16 (d)		
Ho		0.56									
Er		1.87			1.89 (d)				1.33 (d)		
Tm		0.38									
Yb		1.69		1.4 (c)	1.8 (d)				1.19 (d)	1.59 (c)	1.48
Lu		0.25		0.34 (c)					0.176 (d)	0.262 (c)	0.23
Hf		1.97		2.15 (c)						2 (c)	
Ta		0.25						2			
W ppb		480						0.27		0.27 (c)	
Re ppb	0.044 (g)										
Os ppb	<.0023 (g)										
Ir ppb	0.0285 (g)	0.4 (k)				1.55 (g)					0.07
Au ppb	5 (g)	16				88 (g)		12 (g)			0.97
Tl ppb	12.9 (g)	12 (l)				13.4 (g)		11 (g)			
Bi ppb	0.7 (g)	2 (l)				3.7 (g)		1.6 (g)			
Th ppm		0.39	<b>Morgan 73</b>	<b>Chen 86</b>	<b>Chen 86</b>					0.35 (c)	
U ppm	0.129 (g)	0.116	0.465 (e)	0.439 (d)	0.398 (d)						
			0.112 (e)	0.12 (d)	0.099 (d)			0.171 (g)			

technique (a) semi-micro wet chem., (b) emission spec., (c) INAA, (d) isotope dilution mass spec., (e) wet chem., (f) XRF, (g) RNAA

(h) INAA of less than 44 micron fraction, (i) mistake(?) see note in text, (j) Dreibus et al 1985, (k) Burghel 1983, (l) from McSween 1985, (m) elec. probe, fused sample

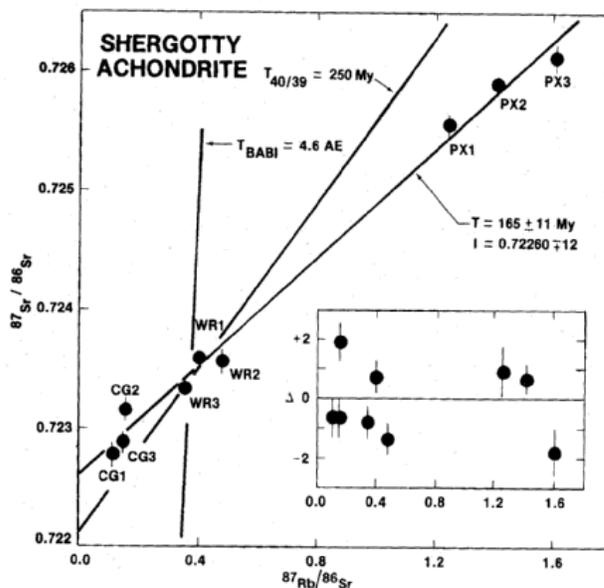
Table V-1. Composition of Shergotty (Continued)

	Schmitt 72	Schmitt 72	Schmitt 72	Laul 86	Laul 86	Laul 86	Laul 86	Laul 86	Laul 86	Stolper 79	Jagoutz86	Jagoutz86
weight	47 mg	915 mg	1.457 g	72 mg	90 mg	139.8 mg	130.7 mg	94 mg	240 mg			
SiO <sub>2</sub> %	(i)	(i)	(i)			49.5 (f)				50.4 (m)		
TiO <sub>2</sub>				0.8 (c)	0.7 (c)	0.87 (f)				0.81 (m)		
Al <sub>2</sub> O <sub>3</sub>				7.14 (c)	6.8 (c)	7.59 (f)				6.89 (m)		
Fe <sub>2</sub> O <sub>3</sub>												
FeO	16.21 (c)	14.15 (c)		19.6 (c)	19.9 (c)	19.8 (c)	20.1 (c)			19.1 (m)		
MnO	0.53 (c)	0.2 (c)		0.52 (c)	0.535 (c)	0.518 (c)	0.54 (c)			0.5 (m)		
CaO				9.52 (c)	9.72 (c)	9.63 (f)	9.88 (c)			10.1 (m)		
MgO				9.5 (c)	9 (c)	8.95 (f)				9.27 (m)		
Na <sub>2</sub> O	1.71 (c)	1.81 (c)	1.25 (c)	1.4 (c)	1.3 (c)	1.47 (c)	1.28 (c)			1.37 (m)		
K <sub>2</sub> O				0.19 (c)	0.15 (c)	0.189 (c)	0.165 (c)			0.16 (m)		
P <sub>2</sub> O <sub>3</sub>						0.72 (f)						
<b>sum</b>						<b>98.52</b>				<b>98.6</b>		
Li ppm						3.3 (c)						
C						430						
F												
S						1570						
Cl						108 (c)						
Sc	49 (c)	35 (c)	26 (c)	54 (c)	56.5 (c)	53.8 (c)	57.8 (c)					
V				260 (c)	265 (c)							
Cr		350 (c)		2616 (c)	2821 (c)	2923 (c)	2675 (c)					
Co	1150 (c)	62 (c)	960 (c)	37.5 (c)	38.5 (c)	37.9 (c)	39.5 (c)	37.2 (g)	37.2 (g)			
Ni				70 (c)	70 (c)	81 (c)	88 (c)					
Cu		139 (c)				26 (c)						
Zn				67 (c)	68 (c)			69.8 (g)	68.4 (g)			
Ga						17.6 (c)	16.5 (c)	17.5 (g)	15.7 (g)			
Ge												
As						0.025 (c)						
Se								0.38 (g)	0.4 (g)			
Br						0.89 (c)	0.8 (c)					
Rb								7.27 (g)	6.11 (g)			
Sr				54 (c)	45 (c)					6.61 (d)	7.53 (d)	
Y										60.12 (d)	50.21 (d)	
Zr				67 (c)	50 (c)							
Nb												
Mo						0.37 (c)						
Pd ppb												
Ag ppb								10.5 (g)	6.8 (g)			
Cd ppb								44 (g)	14 (g)			
In ppb								25 (g)	23 (g)			
Sb ppb								<20 (g)	8.9 (g)			
Te ppb								19 (g)	4.3 (g)			
I ppm						0.036 (c)						
Cs ppm						0.48 (c)	0.42 (c)	0.46 (g)	0.4 (g)		0.53 (d)	0.56 (d)
Ba				32 (c)	27 (c)	40 (c)	39 (c)					
La				2.44 (c)	1.95 (c)	2.44 (c)	1.97 (c)					
Ce				5.8 (c)	4.7 (c)	6.4 (c)	5.6 (c)					
Pr				0.88 (c)	0.7 (c)							
Nd				4.2 (c)	3.3 (c)	4.7 (c)	4.3 (c)				4.18 (d)	3.45 (d)
Sm				1.6 (c)	1.3 (c)	1.66 (c)	1.46 (c)				1.63 (d)	1.4 (d)
Eu				0.65 (c)	0.55 (c)	0.65 (c)	0.55 (c)					
Gd				2.6 (c)	2.1 (c)	2.8 (c)	2.5 (c)					
Tb				0.52 (c)	0.41 (c)	0.52 (c)	0.42 (c)					
Dy				3.7 (c)	3 (c)	4.8 (c)	3.1 (c)					
Ho				0.73 (c)	0.6 (c)	0.86 (c)	0.8 (c)					
Er												
Tm				0.3 (c)	0.25 (c)	0.31 (c)	0.3 (c)					
Yb				1.8 (c)	1.5 (c)	1.79 (c)	1.62 (c)					
Lu				0.26 (c)	0.22 (c)	0.26 (c)	0.24 (c)					
Hf				2.15 (c)	1.5 (c)	2.23 (c)	1.83 (c)					
Ta				0.29 (c)	0.18 (c)	0.27 (c)	0.23 (c)					
W ppb						500 (c)	400 (c)				380.4 (d)	
Re ppb												
Os ppb												
Ir ppb				<5 (c)	<5 (c)	<3 (c)	<3 (c)					
Au ppb				<6 (c)	<6 (c)	0.9 (c)	6 (c)	5.4 (g)	0.81 (g)			
Tl ppb								14 (g)	0.15 (g)			
Bi ppb								1.2 (g)	0.47 (g)			
Th ppm				0.37 (c)	0.25 (c)	0.37 (c)	0.29 (c)					
U ppm				0.095 (c)	0.095 (c)	0.095 (c)	0.095 (c)	0.13 (g)	0.055 (g)			

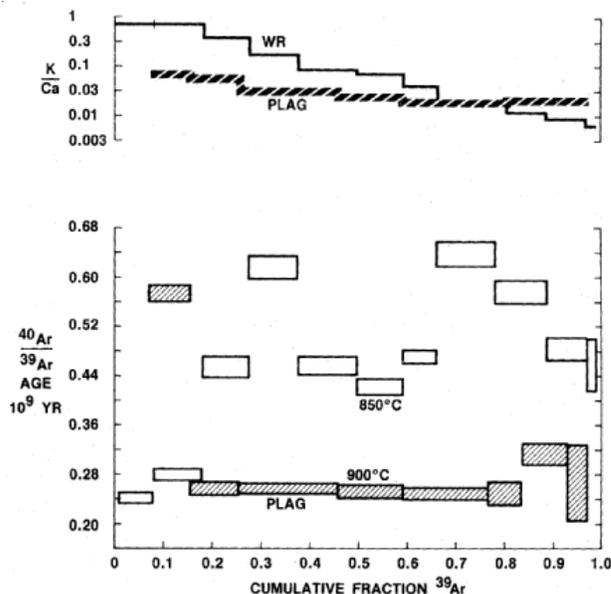
Lee & Halliday 97  
1.856 (d)

**Table V-2. Composition of Shergotty (cont.)**

reference weight	Lodders 98 average	Barrat 2001 90.1 mg.	Blichert-Troft 99 72 mg 54 mg		
SiO <sub>2</sub>	51.3				
TiO <sub>2</sub>	0.82	0.86	(a)		
Al <sub>2</sub> O <sub>3</sub>	6.88	6.51	(a)		
FeO	19.4	18.77	(a)		
MnO	0.52	0.56	(a)		
CaO	9.6	10.28	(a)		
MgO	9.3	8.72	(a)		
Na <sub>2</sub> O	1.39	1.37	(a)		
K <sub>2</sub> O	0.17				
P <sub>2</sub> O <sub>5</sub>	0.67				
sum	100.05				
Li ppm	4.5				
Sc	52	54	(b)		
V	290				
Cr	1350				
Co	40	35	(b)		
Ni	79	66	(b)		
Cu	16	12.3	(b)		
Zn	69	61	(b)		
Ga	16	14.31	(b)		
Ge	0.73				
As	0.025				
Se	0.38				
Br	0.88				
Rb	6.4	5.57	(b)		
Sr	48	40	(b)		
Y	19	14.26	(b)		
Zr	57	59.65	(b)		
Nb	4.6	2.68	(b)		
Mo	0.37				
Pd ppb	1.7				
Ag ppb	11.4				
Cd ppb	28				
In ppb	26				
Sb ppb	5.2				
Te ppb	3.3				
I ppm	0.043				
Cs ppm	0.44	0.42	(b)		
Ba	34	25.6	(b)		
La	2.16	1.56	(b)		
Ce	5.45	3.73	(b)		
Pr	0.81	0.568	(b)		
Nd	4.2	2.97	(b)		
Sm	1.47	1.18	(b)		
Eu	0.6	0.479	(b)		
Gd	2.54	1.94	(b)		
Tb	0.48	0.381	(b)		
Dy	3.5	2.53	(b)		
Ho	0.71	0.548	(b)		
Er	1.88	1.52	(b)		
Tm	0.3				
Yb	1.63	1.32	(b)		
Lu	0.26	0.202	(b)	0.183	0.182 (c)
Hf	2	1.63	(b)	1.77	1.77 (c)
Ta	0.25	0.17	(b)		
W ppb	460	190	(b)		
Re ppb	0.044				
Os ppb	0.4				
Ir ppb	0.057				
Au ppb	0.92				
Tl ppb	0.16				
Bi ppb	1.1				
Th ppm	0.38	0.293	(b)		
U ppm	0.105	0.068	(b)		
technique	(a)	(b)	(c)	(d)	



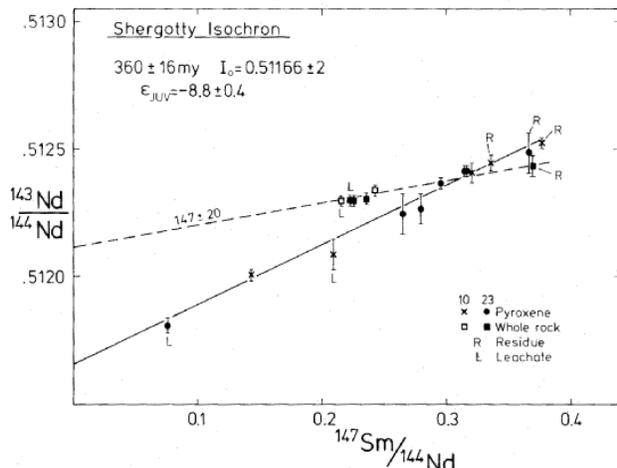
**Figure V-7.** Rb-Sr isochron diagram for mineral separates and whole rock samples from Shergotty. This is figure 1 in Nyquist et al. 1979, GCA 43, 1059.



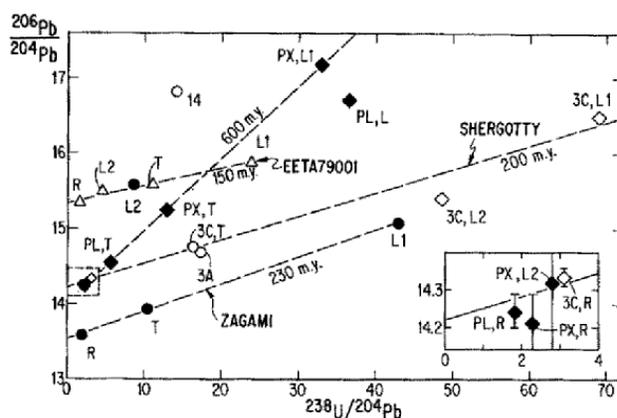
**Figure V-8.** Ar plateau diagram for the age of Shergotty meteorite. This is figure 1 in Bogard et al. 1979, GCA 43, 1049.

Ma for Th-Pb. Sano *et al.* (2000) used the ion microprobe to date phosphates by U-Pb ( $217 \pm 110$  Ma) and Th-Pb ( $189 \pm 83$  Ma).

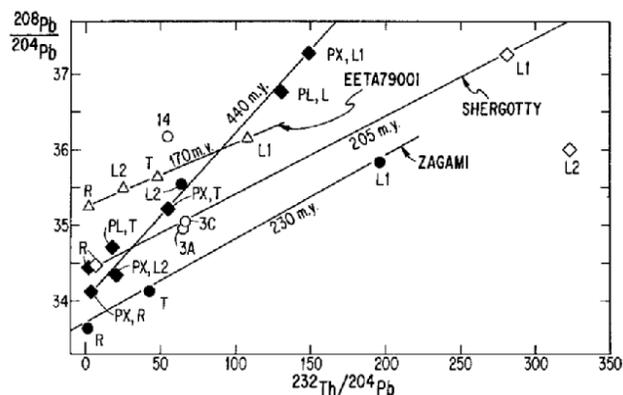
There are many more interpretations of the age data for Shergotty than can be summarized here (*see Jones 1986, 1989 for an interesting approach*), but Nyquist *et al.* (2001) conclude that the **crystallization age of Shergotty is  $165 \pm 4$  Ma** ( $\lambda_{Rb} = 1.402 \times 10^{-11}$  year<sup>-1</sup>). Note that by careful petrography, Müller (1993) concluded that “*the event around 160 Ma is not responsible for the shock metamorphism displayed by Shergotty, but may be the crystallization age.*” However, it is safe to say, that if we only had Shergotty, and didn't have the other Martian meteorites, we would not know what its age was!



**Figure V-9.** Sm-Nd isochron diagram for pyroxene separates and their leachates from Shergotty. This is figure 6 in Jagoutz and Wänke 1986, GCA 50, 946.



**Figure V-10.** U-Pb isochron diagram for Shergotty from Chen and Wasserburg 1986, GCA 50, 959.



**Figure V-11.** Th-Pb isochron diagram for Shergotty from Chen and Wasserburg 1986, GCA 50, 959.

### Cosmogenic Isotopes and Exposure Ages

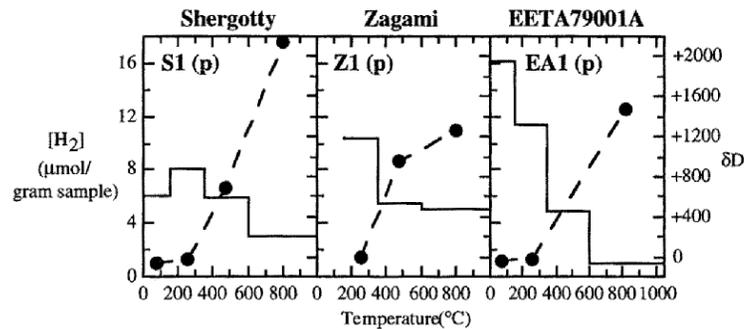
Heymann *et al.* (1968) reported an exposure age of ~2 Ma and Bogard *et al.* (1984b) calculated an exposure age of ~2.6 Ma for Shergotty. Nishiizumi *et al.* (1986b) reported an exposure age of 2.2 Ma. Pal *et al.* (1986) determined an exposure age of  $2.7 \pm 0.9$  Ma using <sup>10</sup>Be. From cosmic-ray produced <sup>3</sup>He, <sup>21</sup>Ne and <sup>38</sup>Ar, Eugster *et al.* (1996) calculated an exposure age for Shergotty of 2.8 Ma (2.5 Ma using <sup>3</sup>He only) and concluded that Shergotty was “*ejected from Mars simultaneously with the other basaltic shergottites QUE94201 and Zagami*” about 2.6 Ma ago. Terribilini *et al.* (1998) determined exposure ages; 2.56 Ma from <sup>3</sup>He, 3.56 Ma from <sup>21</sup>Ne and 2.54 Ma from <sup>38</sup>Ar. Terribilini *et al.* (2000) and Eugster *et al.* (2002) reported 2.71 Ma and  $3.05 \pm 0.5$  Ma from <sup>81</sup>Kr measurements (respectively).

### Other Isotopes

Taylor *et al.* (1965) found that the oxygen isotopes <sup>18</sup>O/<sup>16</sup>O in Shergotty were different from howardites and eucrites. Clayton and Mayeda (1983, 1996) reported the oxygen isotopes for Shergotty and revised the data of Clayton *et al.* (1976). Clayton and Mayeda (1986), Romanek *et al.* (1998) and Franchi *et al.* (1999) have reported additional analyses, including mineral separates. Clayton (1993) reports the <sup>18</sup>O/<sup>16</sup>O composition of plagioclase and pyroxene from Shergotty and calculated the equilibrium temperature. Recently, Weichert *et al.* (2001) have precisely determined the oxygen isotopes in Shergotty.

Watson *et al.* (1994) reported the deuterium contents of hydrous amphiboles in Shergotty. Leshin *et al.* (1996) found water released from Shergotty had high D/H ratios (figure V-12).

Fallick *et al.* (1983) reported  $\delta^{15}N$  as low as -40 ‰ for

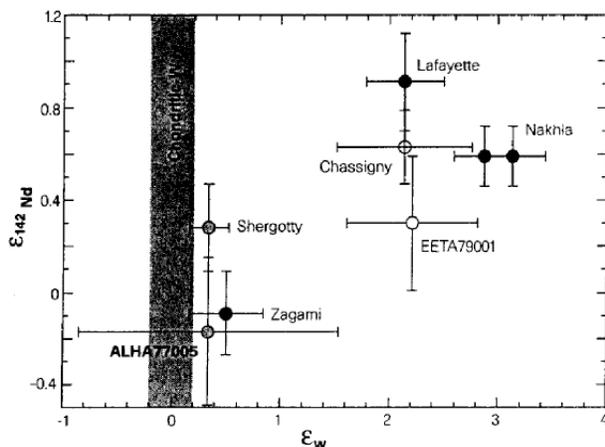


**Figure V-12.** Hydrogen isotopic composition of water released from Martian meteorites including Shergotty. This is figure 3 in Leshin *et al* 1996, *GCA* **60**, 2641.

some steps of combustion. However, Becker and Pepin (1986) found that nitrogen was within a few *per mil* of terrestrial when effects of contamination and spallation are considered. Molini-Velsko *et al.* (1986) reported the isotopic composition of Si and found it normal.

Chen and Wasserburg (1986) reported the Pb isotopes in Shergotty and concluded that the parent body (Mars) was enriched in  $^{204}\text{Pb}$  and other volatiles.

Lugmair *et al.* (1996) and Lugmair and Shukolukov (1998) studied the  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  systematics in a bulk sample of Shergotty and found that it gave the same  $^{53}\text{Cr}/^{52}\text{Cr}$  excess of  $0.23 \pm 0.10\epsilon$  as similar data from ALH84001 (figure I-7). Harper *et al.* (1995), Lee and Halliday (1997) and Wiechert *et al.* (2001) reported  $\epsilon_{\text{Nd}}$  and  $\epsilon_{\text{W}}$  that are nearly chondritic for both shergottites (figure V-13). Blichert-Toft *et al.* (1999) found  $\epsilon_{\text{Hf}}$  for Shergotty and Zagami was significantly different from the other shergottites (*and invoked  $\text{P}_2\text{O}_5$ -rich fluids in the Mars mantle!*).



**Figure V-13.** Shergotty and Zagami have chondritic W and Nd. Figure 3 from Lee and Halliday 1997, *Nature* **388**, 856.

Bogard and Garrison (1998) found that the black glass inclusion (*illustrated in the center of the slab, figure V-2*) contains Martian atmosphere, *somewhat different from the measurements reported by Viking (see also data in Garrison and Bogard 1998)*.

Chaussidon and Robert (1999) have determined the isotopic ratios of Li and B.

### Experiments

Dreibus and Wänke (1996) have reported interesting experiments on the leaching of Shergotty with various solutions, showing that the phosphates readily dissolve, releasing many trace elements to the leach (*see section on Radiogenic Isotopes above*). This important experiment is applicable to what may have occurred on the surface of Mars, and *may* help explain the discordance in radiometric age determinations.

Stolper and McSween (1979) experimentally determined the phase equilibria and crystallization sequence for shergottites. Hashimoto *et al.* (1999) have studied the crystallization path of a liquid with Shergotty composition. Hale *et al.* (1999) and McKay *et al.* (2000) have tried to identify the melt composition that would accompany the pyroxenes in Shergotty. Dann *et al.* (2001) determined that *“the phase relations and compositions of the homogeneous magnesian pyroxene cores in Shergotty are most closely approximated by crystallization under  $\text{H}_2\text{O}$ -saturated conditions at 1120 C and 56 MPa, corresponding to dissolved  $\text{H}_2\text{O}$  contents of 1.8 % and a depth of 5 km in the Martian crust.”* Dann *et al.* go on to explain that the Shergotty magma lost water on extrusion onto Mars surface.

Thellier’s method of paleointensity determination was applied to Shergotty (Cisowski, 1986), but the result was inconclusive, probably because of the high degree

of shock suffered by Shergotty. Rochette *et al.* (2001) re-examined the magnetization of Shergotty (and other Martian meteorites), and concluded that pyrrhotite (which carries the remanent magnetism) is easily reset by shock.

Fission-track mapping by Lundberg *et al.* (1988) found that only ~20 % of the U was located in the phosphates.

Bunch and Cohen (1968), Sippel (1971) and Sears and Hasan (1985) have studied the thermoluminescence of maskelynite (figure V-14).

### Shock Effects

The shock history of Shergotty has been much discussed and is important to an understanding of other properties of the meteorite (*i. e.* magnetic and radioisotope data). Duke (1968) concluded that Shergotty could not have been heated above 400°C following the shock. Lambert and Grieve (1984) and Gibbons and Ahrens (1977) concluded that the high index of refraction of maskelynite in Shergotty was the result of two shock events, one that originally produced the maskelynite and a second lower pressure shock thought responsible for the index of refraction. However, Stöffler *et al.* (1986) concluded that only one shock is needed and estimated the shock pressure was  $29 \pm 1$  GPa with a post shock temperature of  $200 \pm 200^\circ\text{C}$  (figure V-15). Müller (1993) concluded that the magnitude of the shock event was not sufficient to reset the Rb-Sr age. Hörz *et al.* (1986) found that Shergotty pyroxenes showed continuous diffraction rings, line broadening and other evidence of substantial lattice disorder. Stöffler *et al.* reported one grain of silica that might have been stishovite (?). However, recent studies by El Goresy *et al.* (1996, 1997, 1998, 2000) are causing a revision in thinking about the shock effects recorded in Shergotty. Based on relic microstructures in silica grains which indicate high pressure polymorphs of silica, El Goresy *et al.* (1998, 2000), Chen and El Goresy (2000) and Sharp *et al.* (1998, 1999) conclude that the peak shock pressure of Shergotty was in excess of 40 GPa, and may have been as high as 90 GPa. However, Stöffler (2000) has vigorously defended the lower pressure indicated by maskelynite. Using TEM studies, Malavergne *et al.* (2001) identified Ca-rich majorite formed at high pressure and high temperature and have also confirmed the melting (flowing) of plagioclase glass. Based on these observations, Malavergne *et al.* conclude that Shergotty experienced “highly heterogeneous shock conditions at the scale of a few micrometers”.

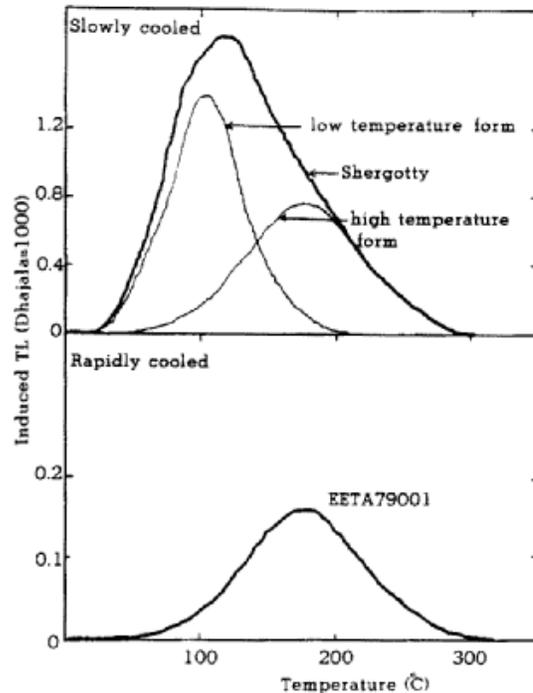


Figure V-14. Experimental thermoluminescence glow curves for Shergotty and EETA79001 meteorites. This is figure 7 from Hasan *et al.* 1985, GCA 50, 1037.

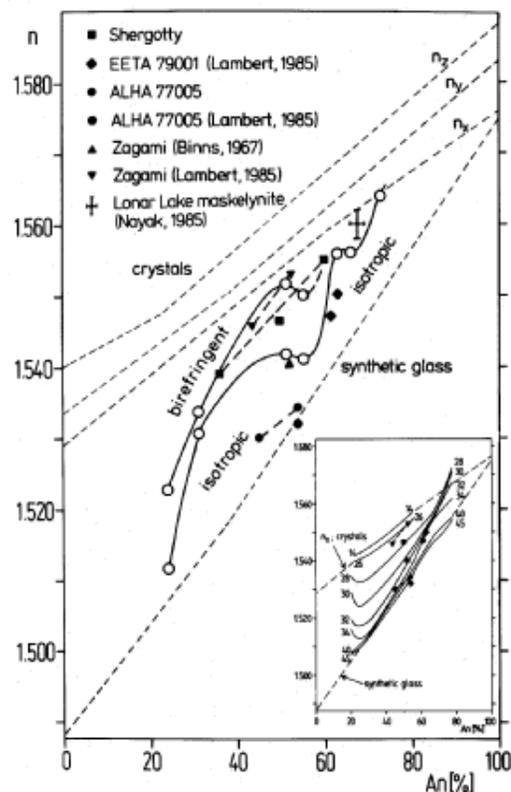
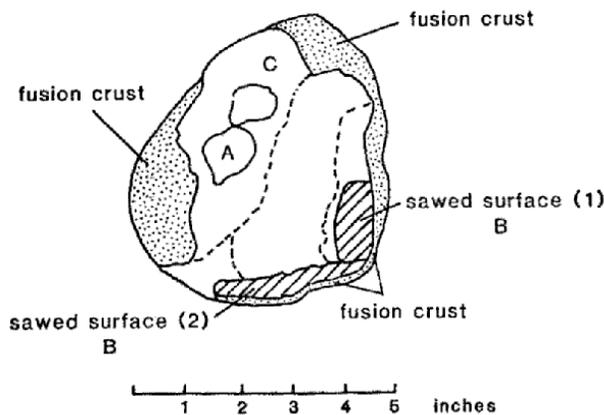


Figure V-15. Refractive index measurements on plagioclase that has been shocked experimentally compared to Martian meteorites. This is figure 12 from Stöffler *et al.* 1986, GCA 50, 897.

Rao *et al.* (1999) have observed enrichment of sulfur in glass in Shergotty and argued that some of the glass in Shergotty might possibly be fused Martian soil.

### Extraterrestrial Weathering

Gooding *et al.* (1988) and Wentworth *et al.* (2000) describe halite, “battered” Ca-sulfate, isolated Mg-chloride and possibly Mg-sulfate, as well as possible tiny flakes of “probable” phyllosilicates. Gibson *et al.* (2001) and McKay *et al.* (2000) observe small (~1 micron) round feature with “smectite-like” clay coatings within selected regions “which have undergone preterrestrial aqueous alteration”.



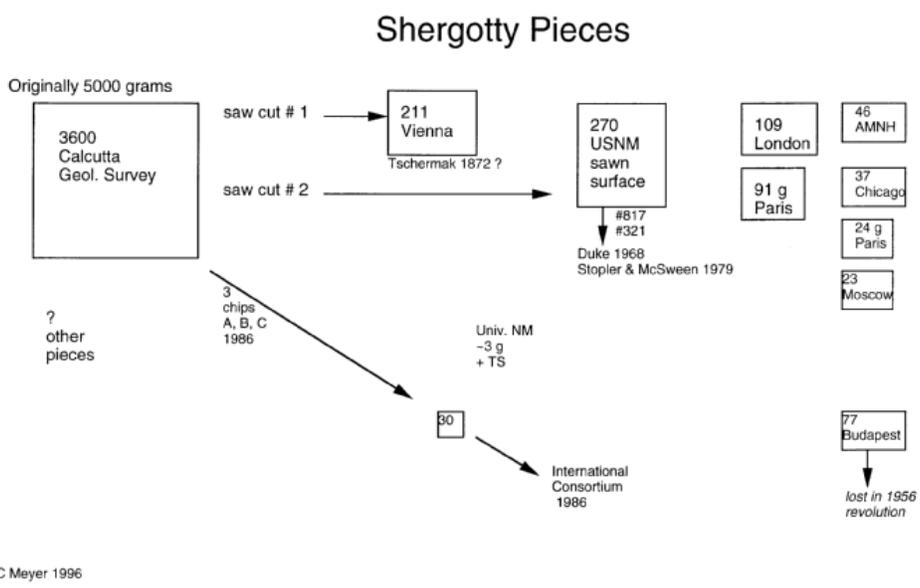
**Figure V-16.** Sketch of main mass of Shergotty showing the location of samples studied by Shergotty Consortium. This is figure 5 in Laul 1986, *GCA* 50, 878.

### Processing

The main mass of Shergotty (~3.6 kg) is curated by the Geological Survey of India, in Calcutta. About 60 % of the surface of this large piece is covered with fusion crust (figure V-1). Over the years, there have been two saw cuts and several large pieces broken off. Duke (1968) refers to more than one piece of Shergotty.

In 1986, J. C. Laul and his colleagues reported the results of the international consortium study on Shergotty in *Geochimica et Cosmochimica Acta*, vol. 50. The samples for the Shergotty Consortium (~30 g) were processed in the curatorial labs at JSC from three chips (labeled A, B and C) provided by the Geological Survey of India. Fragment A (5 g) and fragment C (13 g) were chipped from the main mass next to each other, while fragment B (12 g) was obtained from one of the areas sawn off the other side of the main mass. Figure V-16 shows the location of three chips from the main mass. Powdered samples were prepared from chips B and C for chemical analysis by the consortium (Laul *et al.* 1986). Figure V-17 attempts to show the recent history of the various pieces of the sample.

The large black glass inclusion illustrated in the slab (figure V-2) went from the Smithsonian to Gibson to Bogard. It was found to contain the same rare gasses in the Martian atmosphere as originally found in EETA79001,27, and in fact somewhat different from the measurements reported by Viking.



**Figure V-17.** Distribution of Shergotty meteorite to museums and scientists (preliminary diagram).