

Dhofar 019 – 1056 grams
Depleted Basaltic Shergottite

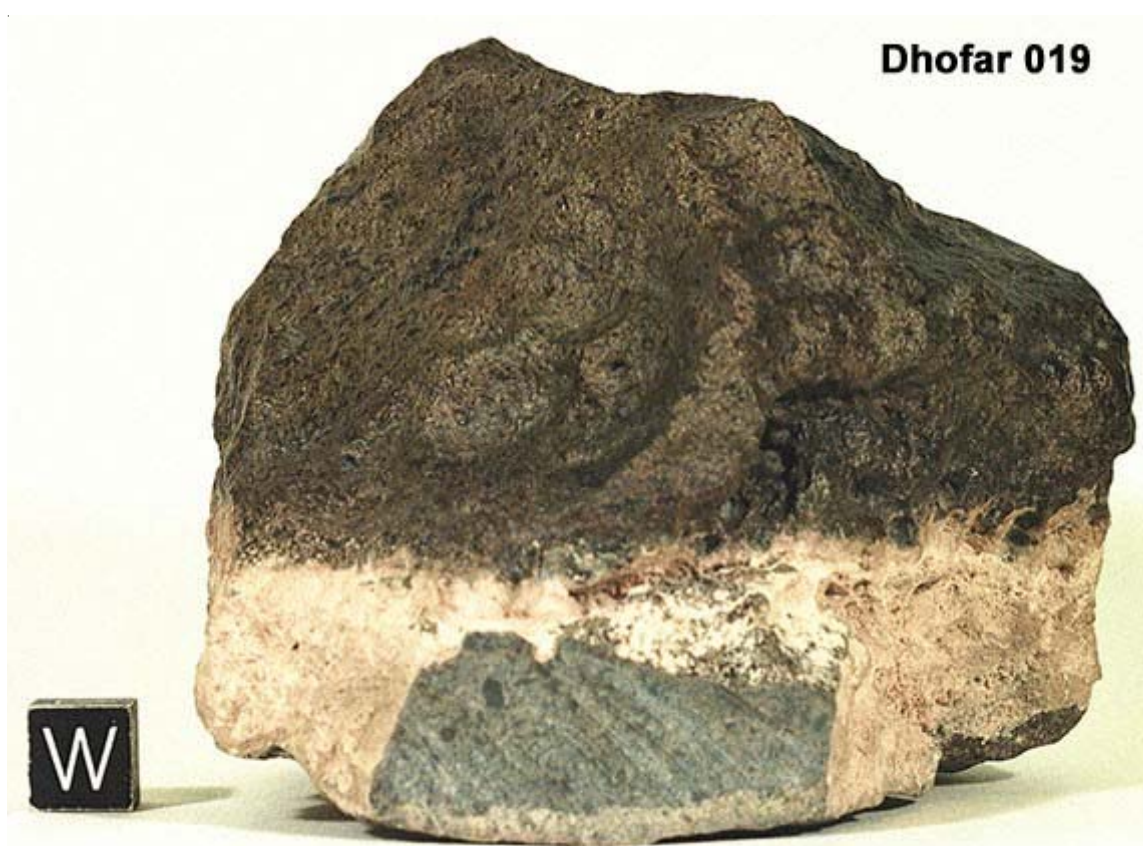


Figure 1: Photograph of Dhofar 019 showing caliche and saw cut (figure kindly provided by Larry Taylor).

Introduction

Dhofar 019 was found in Oman in January 2000 (Grossman 2000). It weighs 1,056 grams and has no fusion crust. Figure 1 shows the main mass and the location of the saw cut providing the first material studied. Cahill *et al.* (2002) find that Dho 019 is heterogeneous with some apparent layering.

Dhofar 019 is found to be rather anomalous when compared with other Martian rocks. It has the oldest age, the greatest exposure to cosmic rays, highest ¹⁸O and lowest siderophile content. The crystallization age of Dho019 is 575 m.y. with a 20 m.y. exposure to cosmic rays.

Petrography

Dhofar 019 is described as a basaltic/doleritic rock consisting of subhedral grains (0.2-0.5 mm) of pyroxene, feldspar converted to maskelynite, and olivine (Taylor *et al.* 2000, 2002). Accessory phases are silica, K-rich

feldspar, whitlockite, chlorapatite, chromite, ilmenite, titanomagnetite, magnetite, and pyrrhotite; secondary phases are calcite, gypsum, smectite, celestite, and Fe hydroxide. Melt inclusions are widely distributed throughout olivine grains and present in a few chromite grains (Cahill *et al.* 2002). Figure 2 is a photo of a slab of Dho019.

Mikouchi and Miyamoto (2001) observe that Dho 019 shows a close mineralogical relationship to EETA 79001, Dar al Gani 476 and Sayh al Uhaymir 005 (figure 3 a,b).

Shock features include fracturing and mosaicism, maskelynite, and rare impact-melt pockets. Planar fractures in olivine occur as two, rarely three, sets of straight, parallel cracks 10-60 microns apart. Pyroxene grains have abundant polysynthetic mechanical twins,



Figure 2: Photo of 3.5 gram slice of Dhofar019 (from website by P. Marmet).

about 1-4 microns in thickness. Badjukov *et al.* (2001) estimate a shock pressure in the range of 30-35 GPa.

The bottom portion of the meteorite was apparently buried in caliche soil (also see nice picture of main mass in Taylor *et al.* 2002). Calcite is present mainly as veins cross-cutting the meteorite.

Mineral Chemistry

Olivine: Lentz and McSween (2001), Mikouchi and Miyamoto (2001) and Taylor *et al.* (2002) have studied the olivine compositions (Fo₇₃₋₂₅). Rare olivine megacrysts (>1.5 mm) have Mg-rich cores (Fo₇₃), but most olivine grains are small (<200 microns) and relatively Fe-rich. The relative high CaO content of olivine (0.35%) is characteristic of extrusive rocks.

Shearer *et al.* (2001) have determined the Ni (170-260 ppm) and Co (220-330 ppm) in olivine grains and find that they were lower than that in olivine from other Martian meteorites. Finally, it must be mentioned that olivines have unexplained “ghosts” in phosphorous zoning (Ennis *et al.* 2010).

Pyroxene: Pigeonite En₄₀₋₇₀Wo₉₋₁₅ is commonly rimmed with augite En₄₀₋₅₀Wo₃₀₋₄₀ (figure 4). No orthopyroxene is found, although it is predicted to have been an early forming mineral (Taylor *et al.* 2002). Al-rich augites are found in melt inclusions.

Feldspar: Plagioclase An₃₆₋₆₈ has been wholly transformed to maskelynite (Badjukov *et al.* 2001).

Modal Mineralogy

	Taylor <i>et al.</i> (2000)	Mikouchi and Miyamoto (2001)	Taylor <i>et al.</i> (2002)
Olivine	9	13.7	10.1
Pyroxene	64	64.6	61.4
Plagioclase	25	19.5	26.1
Phosphates		1	
Opaques		1.2	1.8

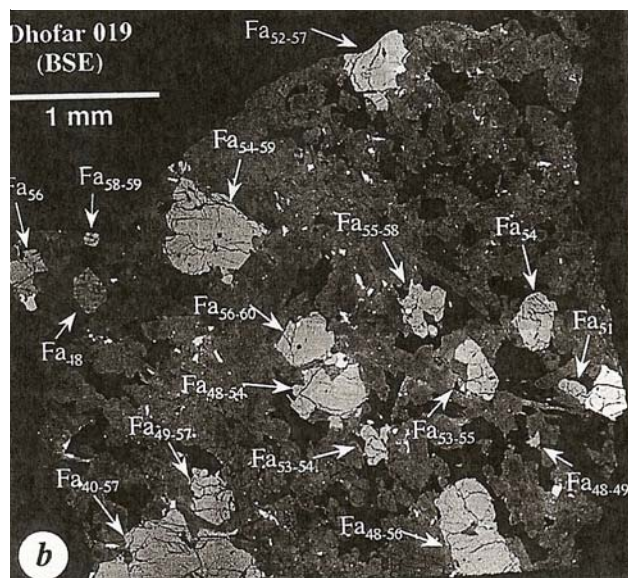
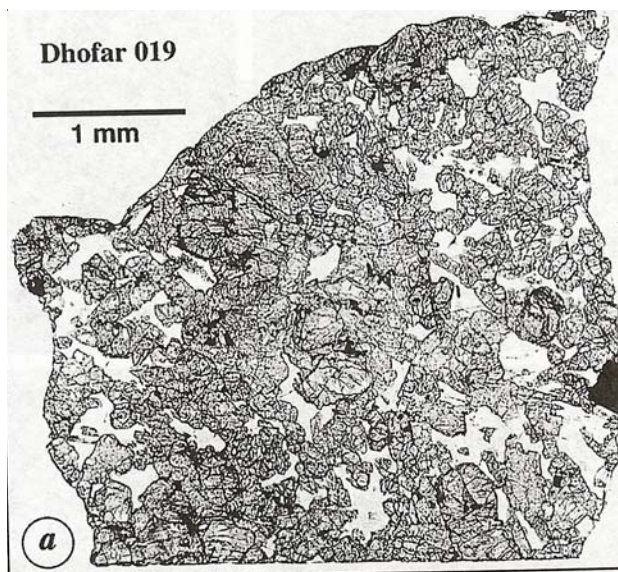


Figure 3 a,b: The best thin section photos of Dhofar019 are found in the paper by Mikouchi and Miyamoto (2002).

Phosphates: Merrillite (whitlockite) is typically homogeneous $\text{Ca}_{8,9}(\text{Mg,Fe})_{1,1}\text{Na}_{0,3}(\text{PO}_4)_7$ (Mikouchi and Miyamoto 2001). Taylor *et al.* (2002) also report analyses of merrillite and of chloro-apatite.

Oxides: Ilmenite and chromite analyses are given in Taylor *et al.* (2002). Chromite cores are overgrown by Cr-ulvöspinel rims.

Sulfide: Taylor *et al.* (2002) determine that the $(\text{Fe}+\text{Ni}+\text{Co})/\text{S}$ ratio of sulfide grains in Dho 019 is ~ 0.87 , corresponding to the formula Fe_7S_8 of pyrrhotite.

Hydrous alteration phases: Taylor *et al.* (2002) report two types of “smectite” in Dho 019, giving rough analyses.

Whole-rock Composition

The chemical composition of Dhofar 019 was reported by Taylor *et al.* (2000, 2002) (Table 1). Neal *et al.* (2001) and Brandon *et al.* (2012) determined the trace element contents, including the PGEs. Dho 019 is interpreted as a “melt product derived from a source already depleted in the incompatible elements and the PGEs” (Neal *et al.* 2001). In addition to being “depleted” in LREE (figure 5), Dho019 is also found to be “depleted” in Rb, Nb, Ta and Th (figure 6).

High CaO , SO_3 , CO_2 and H_2O contents point to a significant terrestrial enrichment in secondary Ca-carbonates, sulfates and clay minerals in the split analyzed. One split had a positive Ce anomaly (figure

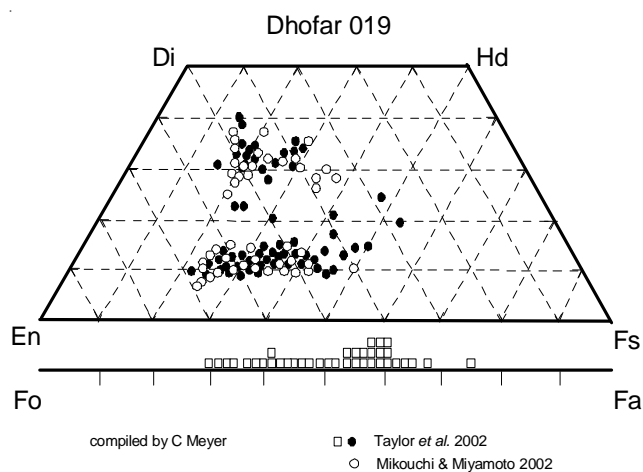


Figure 4: Pyroxene and olivine composition diagram for Dhofar 019 (data replotted from Taylor *et al.* 2002 and Mikouchi and Miyamoto 2002).

5), high Sr and U (figure 6) indicating terrestrial weathering.

Radiogenic Isotopes

Borg *et al.* (2001) determined a Sm-Nd age of 575 ± 7 m.y. for Dhofar 019 (figure 7). The Rb-Sr systematics were slightly disturbed by terrestrial weathering, but a consistent Rb/Sr age of 525 ± 56 m.y. was determined (figure 8). Note that this age is older than that of the other basaltic shergottites (180 - 475 m.y.). Korochantseva *et al.* (2009) found much older ages from K-Ar and Ar-Ar dating.

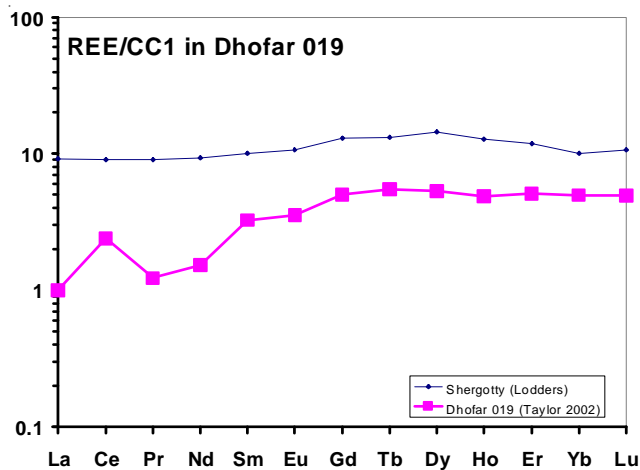


Figure 5: Rare earth element diagram for Dhofar 019 compared with Shergotty (data from Taylor et al. 2002 and Lodders 1998).

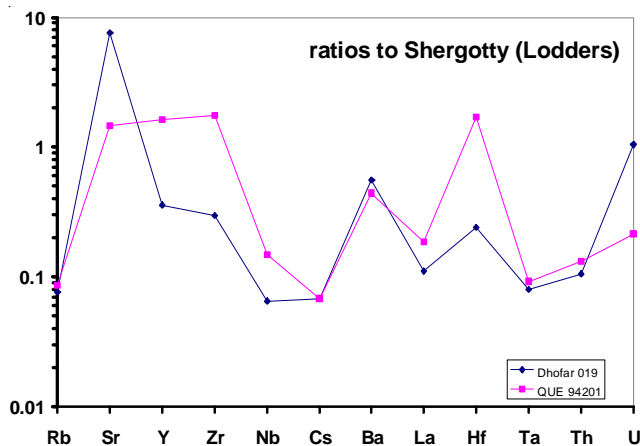


Figure 6: Trace element contents of Dhofar 019 and QUE 94201 divided by composition of Shergotty (for reference).

Cosmogenic Isotopes and Exposure Ages

Shukolyukov *et al.* (2000) determined exposure ages of 18.1 m.y. from ^{21}Ne and 21.4 m.y. from ^{38}Ar , which are the longest so far, for Martian meteorites. Shukolukov *et al.* (2002) determined 20.4 m.y. by ^{81}Kr . Korochantseva *et al.* (2009) determined 15.7 ± 0.7 m.y. by the ^{38}Ar method. Park *et al.* (2001) report a ^{21}Ne exposure age of 12 m.y. Other shergottites have exposure ages in the range of 0.6 to 5 m.y.

Other Isotopes

Taylor *et al.* (2002) reported the oxygen isotopic composition as $\delta^{17}\text{O} = 2.99$ ‰ and $\delta^{18}\text{O} = 5.4$ ‰ with $\Delta^{17}\text{O} = 0.18$ ‰. Of all the Martian meteorites, Dho019 is the most enriched in ^{17}O and ^{18}O .

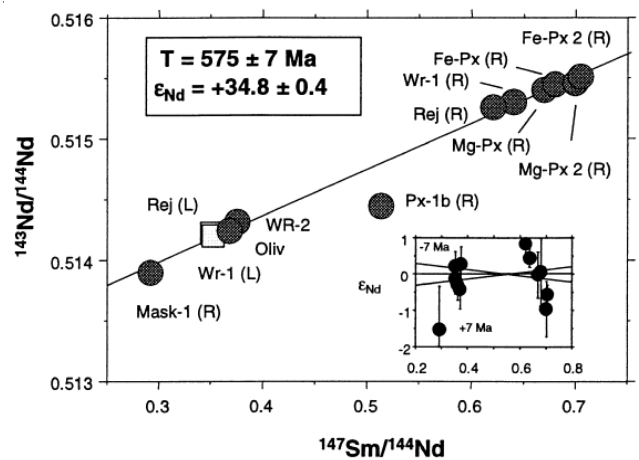


Figure 7: Sm-Nd internal mineral isochron for Dhofar 019 (from Borg *et al.* 2001).

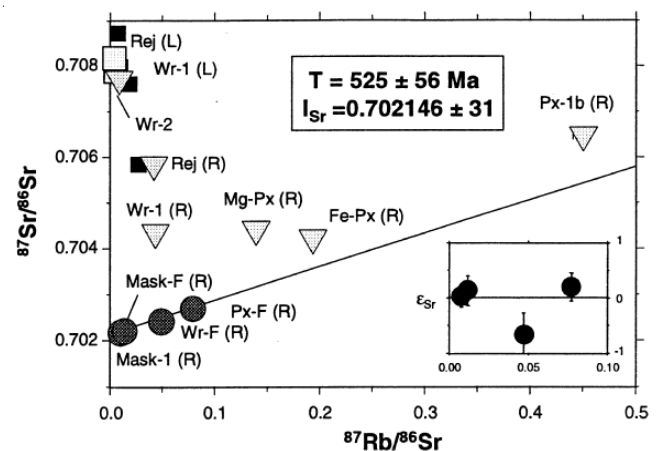


Figure 8: Rb-Sr internal isochron for mineral separates of Dhofar 019 (from Borg *et al.* 2001).

Terrestrial Weathering

There can be no doubt that this meteorite was badly weathered in the desert in Oman (see figure 1). It has calcite, gypsum and a positive Ce anomaly (figure 5). Nanometer-ovoids found within the caliche on the outside of Dho 019 are similar to those found inside (Folk *et al.* 2001).

Extra-terrestrial Weathering ??

Taylor *et al.* (2000) report “numerous zoned smectite-calcite-gypsum “orangettes”, morphologically similar to those in ALH84001 (sic).” It is reported that these secondary phases are located mainly at maskelynite borders with pyroxenes as “mineralogically-zoned grains, which appear to replace maskelynite” (Taylor *et al.* 2002). Taylor *et al.* (2002) illustrate one round patch of “smectite” with intersecting microfault that would seem to suggest that some alteration must be from Mars! (note: This is very hard to distinguish

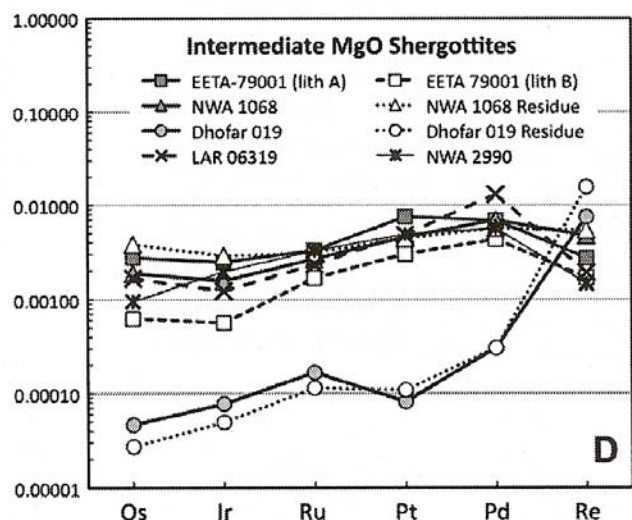


Figure 9: PGE and Re for Dhofar 019 (Brandon et al. 2009).

in this rock, because of evidence for extensive terrestrial weathering).

Processing

The Vernadsky Institute, Moscow, has specimens of 113 grams, 4 grams, and 2 grams, and two thin sections;



Figure 10: This photo of Dho 019 is from the web site by Jim Strobe – 5 gm. piece.

but the main mass remains with the anonymous finder. Photos of slices of Dho019 are showing up on the internet (2012). This rock is apparently unique, so it needs more careful study. Reports that it may be heterogeneous, need to be verified.

References for Dho019



Figure 11: Photo of slab cut from Dhofar019 (from Fectay and Bidaut).

Table 1: Chemical composition Dhofar 019.

reference weight	Taylor 2000	Neal 2001	Neal 2001	Taylor 2002 1 gram	Taylor 2002 115 mg	Taylor 2002 calc.
SiO ₂	49.2			45.52	(b)	48.4
TiO ₂	0.7	0.49		0.594	(b) 0.49	(a) 0.63
Al ₂ O ₃	6.4	6.65		6.72	(b) 6.65	(a) 7.01
FeO	18.4	19.9		17.93	(b) 19.9	(a) 19.1
MnO	0.49	0.48		0.461	(b) 0.48	(a) 0.49
CaO	7.28	9.42		9.27	(b) 9.42	(a) 7.08
MgO	14.6	14.6		14.61	(b) 14.6	(a) 15.5
Na ₂ O	0.92	0.89		0.677	(d) 0.89	(a) 0.72
K ₂ O	0.1			0.053	(d)	0.05
P ₂ O ₅		0.4		0.401	(b) 0.4	(a) 0.41
sum				96.236		100
Li ppm		2.88	2.84		2.86	(a)
Be		0.04	0.02		0.03	(a)
Sc		30.2	32.2	33.8	(c) 31.2	(a)
V		168.5	181.6		175.1	(a)
Cr		3164	3670	3900	(c) 3417	(a)
Co		42.9	46.1	39.1	(c) 44.5	(a)
Ni		63.8	66.8	100	(c) 65.3	(a)
Cu		9.4	9.68		9.54	(a)
Zn		61.9	62.1		62	(a)
Ga		9.81	10.6		10.21	(a)
Se				0.32	(c)	
Br				0.19	(c)	
Rb		0.52	0.46		0.49	(a)
Sr		361	364	285	(c) 363	(a)
Y		6.81	6.75		6.78	(a)
Zr		15.2	19.6	50	(c) 17.4	(a)
Nb		0.29	0.31		0.3	(a)
Mo		0.42	0.63		0.52	(a)
Sb ppb		20	10	40	(c)	
Cs ppm		0.02	0.03	0.32	(c) 0.03	(a)
Ba		20	18.8	70	(c) 19.4	(a)
La	0.2	0.24	0.24	0.3	(c) 0.24	(a)
Ce	0.68	1.48	1.42	1.1	(c) 1.45	(a)
Pr		0.1	0.11		0.11	(a)
Nd		0.65	0.73	1.6	(c) 0.69	(a)
Sm	0.44	0.51	0.45	0.82	(c) 0.48	(a)
Eu	0.081	0.17	0.23	0.14	(c) 0.2	(a)
Gd		0.96	1.01		0.99	(a)
Tb		0.2	0.2	0.22	(c) 0.2	(a)
Dy		1.32	1.28		1.3	(a)
Ho		0.27	0.27		0.27	(a)
Er		0.86	0.75		0.81	(a)
Tm		0.11	0.12		0.12	(a)
Yb	1.29	0.85	0.76	0.74	(c) 0.81	(a)
Lu	0.26	0.13	0.11	0.13	(c) 0.12	(a)
Hf		0.46	0.5	0.7	(c) 0.48	(a)
Ta		0.02	0.02	0.1	(c) 0.02	(a)
W ppb		10	40		30	(a)
Ir ppb		0.127		<9	0.127	(a)
Ru ppb		0.354			0.354	(a)
Rh ppb		0.295			0.295	(a)
Pt ppb		3.969			3.969	(a)
Pd ppb		1.718			1.718	(a)
Th ppm		0.04	0.03		0.04	(a)
U ppm		0.1	0.12		0.11	(a)

technique: a) ICP-MS, b) ICP and XRF, c) INAA, d) AA



Figure 12: Dhofar 019 insitu.