Nakhla – 10 kilograms
Clinopyroxenite
shower, seen to fall

Figure II-1. *Three largest pieces of Nakhla meteorite (1813 grams, 1651 grams and 1318 grams). Note the thin black fusion crust and broken surface. Photograph kindly provided by Gaber M. Naim, Director, Egyptian Geological Survey.*

Introduction

Multiple fragments of the Nakhla meteorite were seen to fall as a shower in the hamlets surrounding the village of El-Nakhla, El-Baharîya in Egypt (near Alexandria) on June 28th, 1911 at 9:00 a.m. Dr. W. F. Hume, Director of the Geological Survey of Egypt, personally visited the site and collected both the evidence of eye-witnesses of the fall and about a dozen specimens including the largest known fragments (Hume 1911; Ball 1912) (figure 1).

The following account is from Attia *et al.* (1955*). "From the evidence of eye-witnesses, it appears that the stones fell over an area of 4.5 kilometers in diameter; and were derived from the explosion of a single meteorite. The explosion seems to be repeated several times and the track of the meteorite was marked by a column of white smoke. The stones buried themselves in the ground to depths ranging from 10-30 cm and the holes caused showed some inclination. Altogether about forty stones, of a total weight of nearly 10 kilograms, were collected. Of these, about half are completely enveloped in a black varnish-like skin of fused matter. Some have one or more of their faces only partially fused, while others exhibit fresh fractures showing greenish-gray crystalline interior. The weights of the individual stones range from 1813 grams in the largest specimen down to about 20 grams in the smallest. The smallest fragment of which the fused skin is entire weighs 34 grams."*

The exact strewn field for the Nakhla shower is unmapped, but is said to be within a diameter of 4.5 km (Prior 1912). Kevin Kichinka has documented the circumstances of the Nakhla fall (Kichinka 1998 a, b). In 1998, Grady and Lindstrom organized for "fully crusted" piece of Nakhla (BM1913,25) to be split at and allocated from JSC in a "clean" nitrogen processing cabinet in order to minimize new contamination and provide samples from the same piece. Over 65 samples have since been allocated from this piece (McBride and Righter 2011).

The crystallization age of Nakhla has been determined to be 1.38 b.y. and it has been exposed to cosmic rays for 11 m.y.

Figure 2: *A fresh face of Nakhla (origin of picture unknown).*

Petrography

Nakhla is an olivine-bearing, clinopyroxenite consisting mostly of augite with less abundant Fe-rich olivine, plagioclase, K-feldspars, Fe-Ti oxides, FeS, chalcopyrite and a hydrated alteration phase that resembles "iddingsite" (Prior 1912; Bunch and Reid 1975; Reid and Bunch 1975; Weinke 1978; Harvey and McSween 1992 b, d; Treiman 1986, 1990, 1993 a, d).

In Nakhla, euhedral and subhedral sub-calcic augite grains (0.5 to 1.0 mm) are set in a fine-grained mesostasis of thin radiating laths of plagioclase, pyroxenes, olivine, magnetite and other minerals (figures
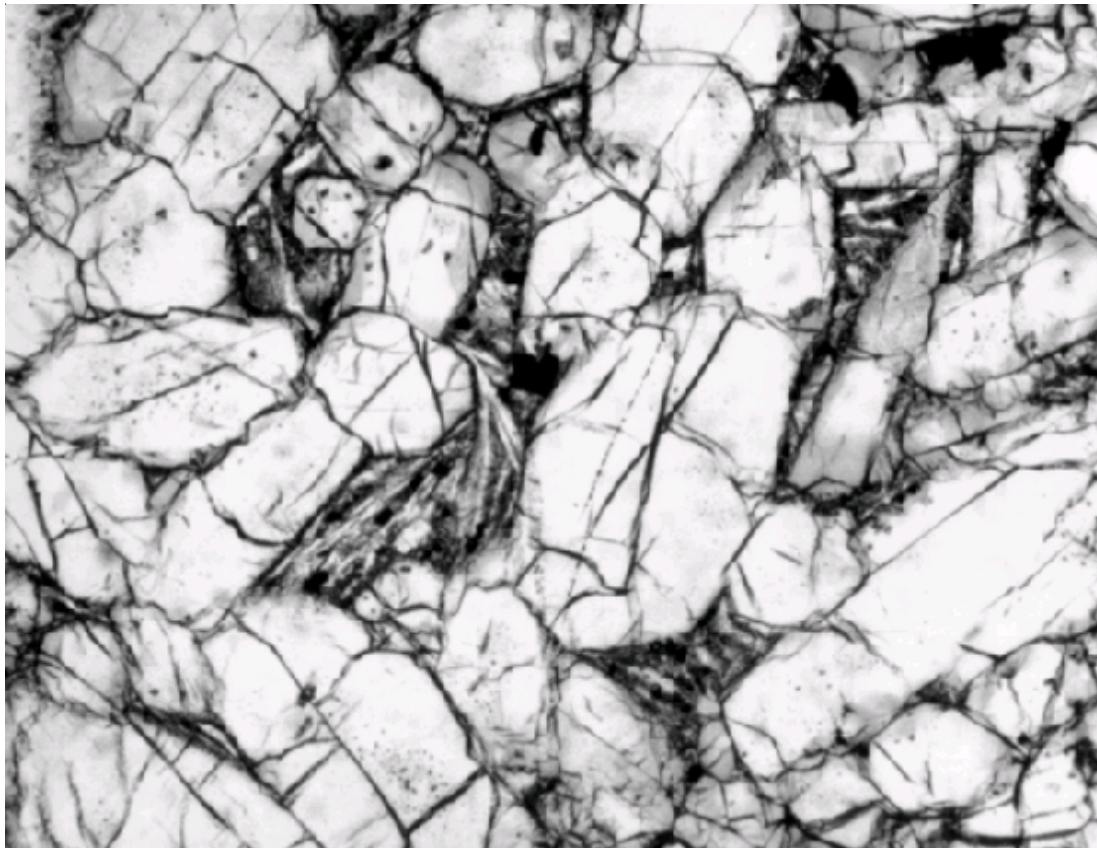
Figure 3. *Photomicrograph of thin section of Nakhla meteorite illustrating close-packed, elongate clinopyroxene crystals and minor mesostasis with lath-like plagioclase. Field of view is 2.2 mm.*

2 and 3**).** Minor subhedral olivine grains up to 2-4 mm are also present (Treiman 1990). Nakamura *et al.* (1982a) observed poikilitic intergrowths between olivines and pyroxenes indicating substantial adcumulus growth.

The nakhlites (Nakhla, Lafayette, Governador Valadares, NWA817, NWA998, Yamoto 000593, Mil03346 and NWA 5790) have been interpreted as cumulates (*i.e*. Bunch and Reid 1975; Gale *et al*. 1975). However, Treiman (1987), Treiman *et al*. (1996) and Lentz *et al.* (1999) found a close comparison of Nakhla with "Theo's flow," which is an extrusive Archean flow in Canada. In fact, Prior (1912) originally observed that the interstitial mesostasis of Nakhla was *"like the matrix of a fine-grained basalt"*. The elongate pyroxenes in the nakhlites are weakly aligned (Berkley

et al. 1980). It is also claimed that the nakhlite meteorites have experienced varying degrees of late-magmatic and sub-solidus diffusive re-equilibration (Harvey and McSween 1992).

The olivine and augite grains in Nakhla frequently contain magmatic, "melt" inclusions (figure 4). These inclusions have mostly re-crystallized and are hard to analyze, but numerous attempts have been made to use them to calculate the composition of the initial magma (Treiman 1986, 1993; Harvey and McSween 1992d; Stockstill *et al*. 2001, 2005; Rost *et al*. 2001). Perhaps the best attempt to "calculate" the parent magma composition is found in Treiman and Goodrich (2001).

Bodnar (1999) and Bridges *et al.* (2000) have reported evidence of *"decrepitated"* fluid inclusions along sealed

Mineralogical Mode (from Lentz *et al*. 1999)

(volume %)

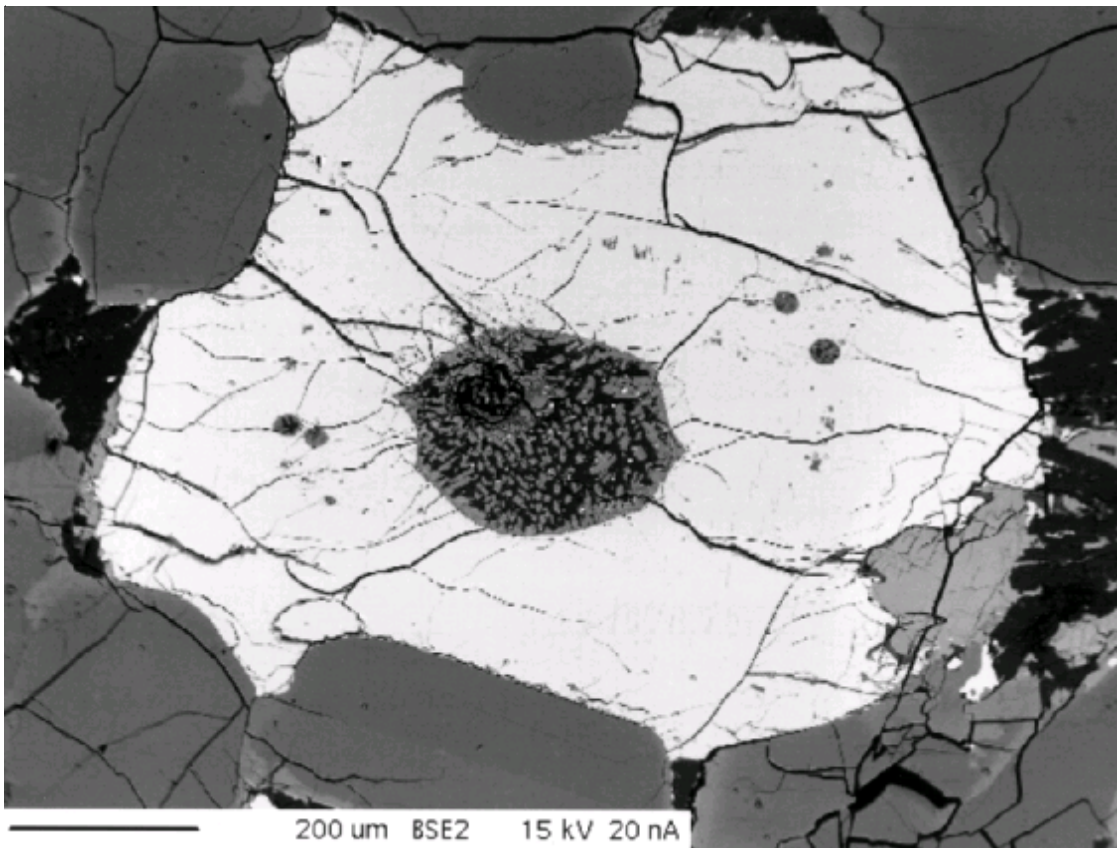|										
Olivine	14.2%	11.9	8.2	5.7	4.6	16	8.5	18	13.2	16
Pyroxene	75.4	83.4	83	85.2	84.4	74.6	80.7	74.1	81	76.8
Mesostasis	10.4	4.7	8.7	9.2	11	9.4	10.8	8	5.8	7.2
Hydrous alteration		*trace*								

Figure 4. *Backscattered electron image of large recrystallized "melt" inclusions in olivine (bright region) in Nakhla (note also the vesicle in the melt inclusion). Olivine is surrounded by close-packed clinopyroxene crystals.*

cracks in pyroxenes in Nakhla.

Delano and Arculus (1980) experimentally determined that Nakhla crystallized at a higher oxygen fugacity than basaltic achondrites. Re/Os fractionation also indicates that the source of Nakhla magma was oxidized (Birck and Allègre 1994). Note that oxidized iron is present in magnetite.

Nakhla has been only mildly shocked with an estimated peak pressure of about 20 GPa (Greshake 1998).

It has been proposed that secondary aqueous alteration of nakhlites may have occurred on Mars (Gooding *et al.* 1991; Bridges *et al.* 2001) *(see sections on "Salts", "Radiogenic Isotopes" and Lafayette "Iddingsite").* McKay *et al.* (2001) illustrate the secondary alteration (submicron) along cracks in Nakhla.

Mineral Chemistry
Olivine: The olivine in nakhlites has higher Fe/Mg (Fo_{25-35}) than that of coexisting pyroxene (En_{60-70})(figure 6). The olivine in Nakhla is zoned in composition, with steep Mg/Fe profiles in the core regions and progressively flatter toward the crystal boundaries (Harvey and McSween 1991). The Ca content of olivine is also zoned, first from low Ca to high, then a decrease believed to correspond with onset of augite crystallization. Nakamura *et al.* (1982) reported REE abundance in olivine, but this may include the REE in magmatic inclusions and attached mesostasis (figure 5). Lentz *et al.* (1999) have carefully analyzed the olivine in Nakhla and Wadhwa and Crozaz (1995) determined REE by ion probe. Smith *et al.* (1983) reported relatively high Ni and Ca contents in olivines and showed that they were not of "plutonic" origin.

Clinopyroxene: The major mineral is augite ($Wo_{40}En_{40}Fs_{20}$). Bunch and Reid (1975), Treiman (1990) and Harvey and McSween (1991) found that the cores of the clinopyroxenes in Nakhla were homogeneous with zoning towards Fe enrichment at the rims, with steep transition zones in between (figure 6). Allen and Mason (1973), Nakamura *et al,* (1982) and Wadhwa and Crozaz (1995a) reported the REE abundances in pyroxene from Nakhla. Lentz *et al.*
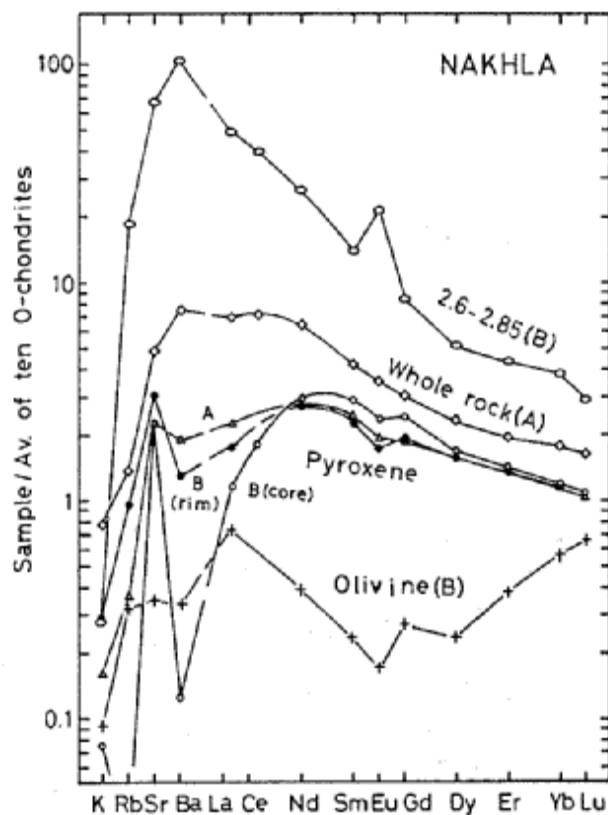
Figure 5. *Chondritic normalized REE and other LIL element abundance patterns for whole rock and mineral separates of Nakhla. This is a copy of figure 2 in Nakamura et al. (1982), GCA* **46**, *1559.*
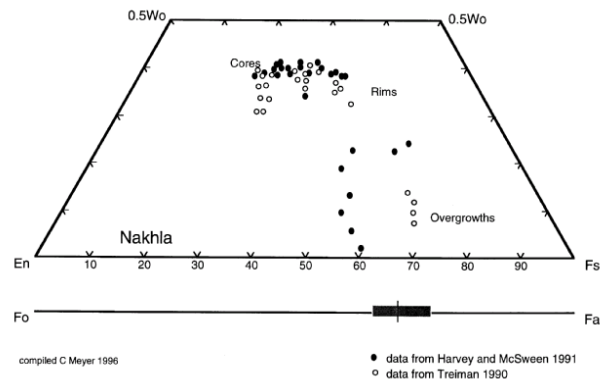

Figure 6. *Pyroxene and olivine composition diagram. Data replotted from Harvey and McSween (1991) and Treiman (1990). Note that olivine phenocrysts have composition in equilibrium with final melt, rather than with the first-formed pyroxene.*

(1999) have analyzed pyroxene in Nakhla and Smith *et al.* (1983) carefully determined the minor element content (Mn, Ti, Al, Cr, Na). Some grains of clinopyroxene show polysynthetic twinning which may have been caused by shock. Greshake (1998) has carefully studied the exsolution in augite in Nakhla. Mikouchi and Miyamoto (1997) have carefully compared the pyroxenes found in the nakhlites. Lentz *et al.* (2002) determined that Li, Be and B abundances increased from core to rims in Nakhla pyroxenes. Varela et al. (1999) and Stockstill et al. (2005) studied the melt inclusions found in augite.

Plagioclase: Bunch and Reid (1975) determined the composition of plagioclase as $An_{34}Ab_{62}Or_4$. In Nakhla, plagioclase is birefringent and apparently was not maskelynitized by shock (Greshake 1998). Lentz *et al.* (2002) determined Li, Be and B in plagioclase.

K-feldspar: Bunch and Reid (1975) reported that potassium feldspar ($Or_{74}Ab_{24}An_2$) occurs in the mesostasis.

Phosphates: Crozaz (1979) studied the U and Th distribution in Nakhla and determined the Th/U ratio in small grains (30 microns) of Cl-apatite. Bridges and Grady (1997) and Protheroe *et al.* (2001) also reported chloroapatite.

Iddingsite: Reid and Bunch (1975) noted the fibrous habit of the alteration in Nakhla and concluded that it was "pre-terrestrial". Ashworth and Hutchison (1975) studied the iddingsite with high-voltage electron microscopy and also argued that it was of extra-terrestrial origin, because it was remobilized by the shock event. Gooding *et al.* (1991) tentatively identified smectite in this "iddingsite" *(see also Lafayette and NWA817).* Papanastassiou and Wasserburg (1974) reported high K (~7 wt. %) in brown "films" in pyroxene. Bunch and Reid (1975) give an analysis of "iddingsite" in Nakhla.

Glass: Interstitial glass has been analyzed by Berkley *et al.* (1980). Gale *et al.* (1975) also reported glass in Nakhla as one of their "mineral" separates.

Magnetite: Ti-rich magnetite with ilmenite exsolution is an important phase in Nakhla (Bunch and Reid 1975, Ashworth and Hutchison 1975). Magnetite is also one of the "mineral" separates analyzed by Gale *et al.* (1975). Weinke (1978) found that the magnetite contained substantial Fe^{+3}. Greshake *et al.* (2000) point out that this requires highly oxidizing conditions, possibly subsequent to initial crystallization.
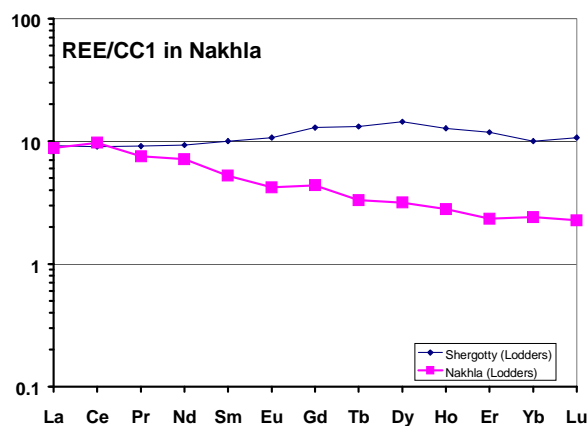
Figure 7. *Chondrite normalized REE abundance patterns for Nakhla, compared with that of Shergotty.*

Figure 8. *Total sulfur contents determined for Martian meteorites. This is figure 2 in Burgess et al. (1989).*

Symplectite: Yamada (1997), Mikouchi and Miyamoto (1997, 1998) Greshake *et al.* (2000) and Wasserman and Bertka (2000) have studied thin lamellar symplectic inclusions composed of augite and magnetite in host olivine.

Ilmenite: Harvey and McSween (1992d) determined the composition of ilmenite in a magmatic inclusion in Nakhla olivine.

Sulfides: Bunch and Reid (1975) observed that the sulfide grains ranged from *"fresh to altered grains that had a weathered appearance"*. They tentatively reported both "stoichiometric" pyrite and FeS (pyrrhotite ?) with 0.2 to 0.5% Ni. Weinke (1978) gave a complete analysis of "troilite". Greenwood *et al.* (1998) report minor chalcopyrite associated with pyrrhotite and have determined the isotopic composition of S.

Carbonates: Chatzitheodoridis and Turner (1990) and Bridges and Grady (1998a, b, 1999, 2000) reported analyses of siderite in Nakhla and found some grains that were extremely high in MnO (~20%). Saxton *et al.* (1997, 2000) determined that the $\delta^{18}O = +34‰$ in Mn-rich siderite grains in Nakhla is higher than any other Martian carbonates. Grady *et al.* (1995) reported $\delta^{13}C = +50‰$ in siderite from Nakhla.

Salts: Wentworth and Gooding (1988a,b, 1989), Chatzitheodoridis and Turner (1990) and Gooding *et al.* (1991) have reported minor, but important, amounts of Ca-carbonate, Ca-sulfate, Mg-sulfate, NaCl, and "rust" including a clay mineral tentatively identified as smectite *(see discussion in "Other Isotopes")*. Bridges and Grady (1997) reported abundant (1%),
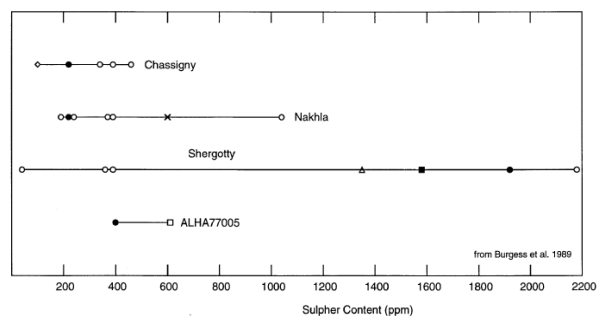
large grains of halite (400 microns) with included grains of plagioclase, silica, chloroapatite, siderite and anhydrite and initially argued that this halite was igneous in origin and formed from the magma! On further evidence, Bridges and Grady (1999, 2000) found that the halite-siderite-anhydrite-chloroapatite assemblages in Nakhla instead indicated *"progressive evaporation"* of an acidic brine on Mars.

Wentworth *et al.* (2001) illustrate lath-like, gypsum/anhydrite with evidence of desiccation and/or weathering.

Whole-rock Composition

Major element analyses of Nakhla were reported by Prior (1912), McCarthy *et al.* (1974), Dreibus *et al.* (1982) and Kong *et al.* (1999)(Table 1). Nakhla is ultra-mafic and very poor in Al_2O_3 (~1.6%). Schmitt and Smith (1963) first reported REE analyses of Nakhla and Lafayette and recognized that they had REE patterns similar to terrestrial basalts! Weinke (1978) and Wang *et al.* (1998) determined trace element analyses of Nakhla. The REE analysis by Nakamura *et al.* (1982) is plotted in figure 5 and Dreibus *et al.* (1982) in figure 7. Laul *et al.* (1971) found that Nakhla had volatile element abundances similar to those in ocean ridge basalts. Treiman (1987), Treiman *et al.* (1996), Friedman *et al.* (1997) and Lentz *et al.* (1999) found a close comparison of chemistry, texture and mineralogy of Nakhla with Theo's flow, which is an extrusive Archean flow in Canada.

In addition to the data in table 1, Clark *et al.* (1967) determined 40 ppb U. Curtis *et al.* (1980) determined two values for B (4.6 and 255 ppm) for the Nakhla meteorite. Gibson and Moore (1983) determined 1040 ppm S for one piece and Gibson *et al.* (1985) determined values of 260, 200, 330 and 360 ppm S for additional
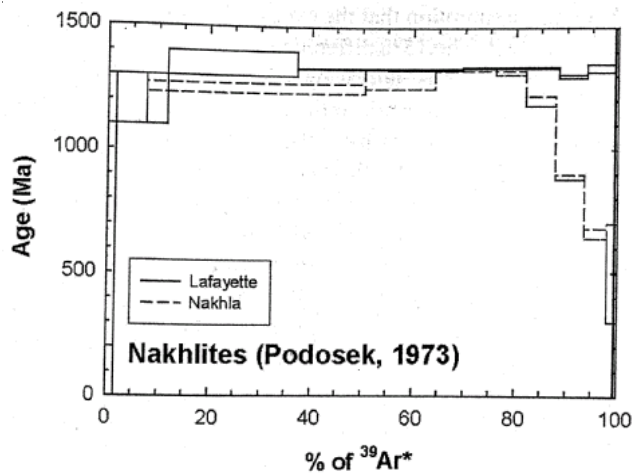
Figure 9: Ar plateau diagram for Nakhla and Lafayette (from Podosek 1973).

Figure 10: Argon plateau age for Nakhla (from Swindle and Olson 2004).
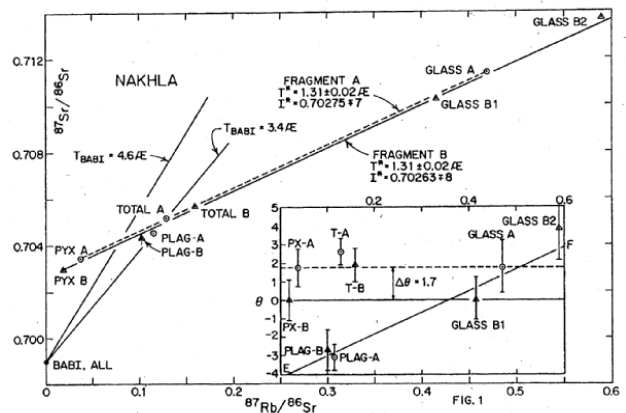
Figure 11: Rb-Sr isochrons for two small fragments of Nakhla (from Papanastassiou and Wasserburg 1974).

pieces. Burgess *et al.* (1989) determined 220 ppm S and found that it was released over a wide range of temperatures (figure 8). Mermelengas *et al.* (1979) determined 23 ppb Pd. Smith *et al.* (1977) determined 90 ppb Te. Ehmann and Lovering (1967) determined 0.22 to 0.25 ppm Hg, but this is probably laboratory contamination, as Weinke (1978) determined only 0.7 ppb Hg. Wang *et al.* (1997) reported a wide range of volatile trace elements with no apparent difference between Antarctic and non-Antarctic Martian meteorites.

The nakhlites contain a minor amount of H_2O as hydrous silicate minerals (Ashworth and Hutchison 1975; Bunch and Reid 1975; Gooding *et al.* 1991; Treiman *et al.* 1993). These altered areas are probably the same as the "brownies" observed by Papanastassiou and Wasserburg (1974). Karlsson *et al.* (1992) reported 0.114 wt % H_2O for Nakhla. Watson *et al.* (1994) also reported 0.11 % H_2O. Gooding *et al.* (1990) determined the thermal release pattern for several volatile species.

Papanastassiou and Wasserburg (1974) noted that the Rb/Sr and K/U of the parent planet for Nakhla were similar to the ratios for the Earth.

Dreibus *et al.* (1999), Sawyer *et al.* (2000) and Gilmour *et al.* (2001) have reported the composition of water-soluble salts leached from Nakhla.

Radiogenic Isotopes

Stauffer (1962) originally reported a K-Ar age of 1.3 b.y. for Nakhla. Using ^4He and ^{40}Ar, Ganapathy and Anders (1969) calculated "gas retention ages" of 0.77 b.y. and 1.4 ± 0.3 b.y. respectively for Nakhla. Podesek (1973) reported an Ar39-40 age of ~ 1.3 b.y. (figure 9). Swindle and Olson (2004) obtained relatively flat Ar plateaus at 1.332 ± 10 b.y. (figure 10). K-Ar ages are also reported for different separates by Gilmour *et al.* (1997).

Using Rb-Sr ($\lambda_{Rb} = 1.39 \times 10^{-11}$ year^{-1}), Papanastassiou and Wasserburg (1974) determined an age of about 1.31 - 1.37 b.y. (figure 11) and Gale *et al.* (1975) 1.24 ± 0.01 b.y. (figure 12).

Nakamura *et al.* (1977, 1982) used the Sm-Nd system to determine an age of 1.26 ± 0.07 b.y. (figure 13).
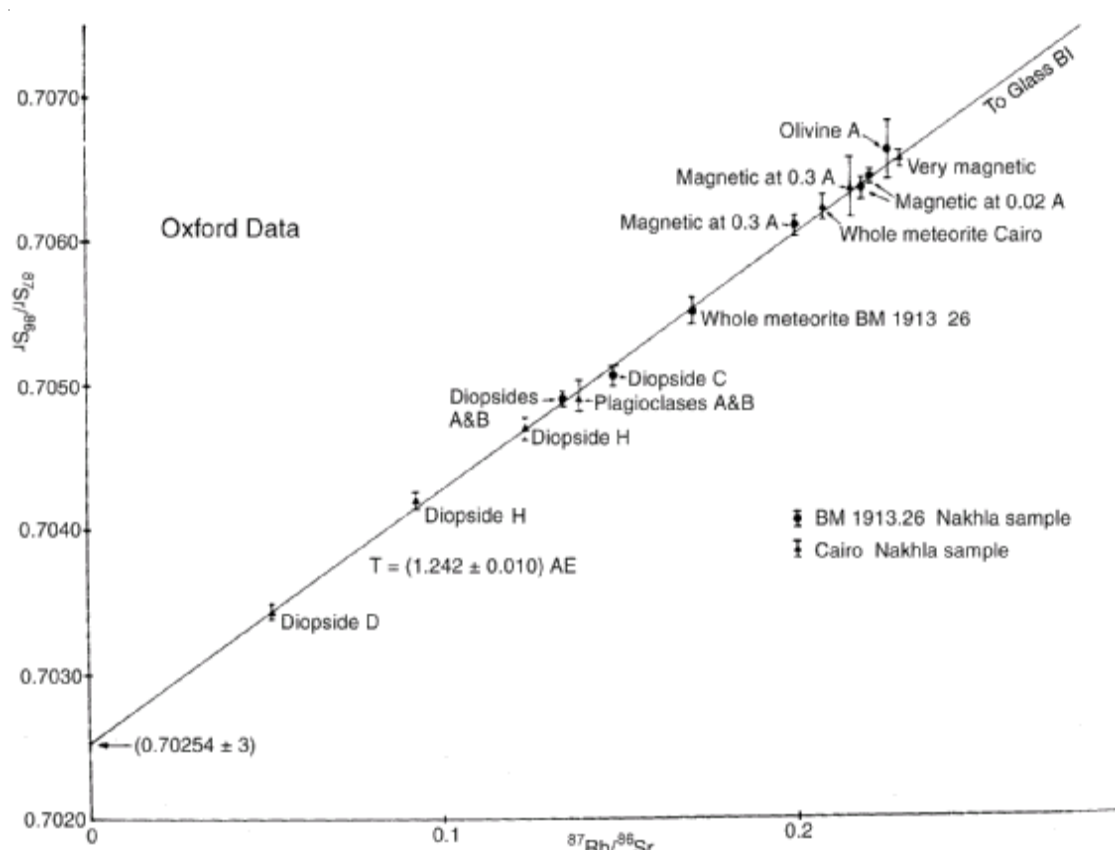
Figure 12. *Rb-Sr mineral diagram for Nakhla determined by Gale et al. (1975).*

Hutchison *et al.* (1975), Nakamura *et al.* (1982) and Chen and Wasserburg (1986b) tried to determine a U-Pb age (figure 14) — without agreement. **Finally, in 2010, Shih et al. dated Nakhla by Sm-Nd internal isochron obtaining an age of 1.38 ± 0.07 b.y.** (figure 15).

One might suppose that all the nakhlites should have the same exact age, but the ages obtained have not been concordant within the quoted precision of the measurements. Gooding *et al.* (1991) discuss the effect that pre-terrestrial aqueous alteration (weathering) might have had on the disturbance of the Rb-Sr system. K-Ar ages of iddingsite were reported by Swindle *et al.* (1997, 2004) *(see also discussion in Lafayette).*

Cosmogenic Isotopes and Exposure Ages
All of the nakhlites have similar exposure ages. Using ^3He, ^{21}Ne and ^{38}Ar, Ganapathy and Anders (1969) calculated an average cosmic-ray exposure age of 10.1 m.y. for Nakhla (see figure 12). Using new production rates, Bogard (1995) calculated 12 m.y. from the ^{21}Ne data and 11 Ma from the ^3He data. Eugster *et al.* (2002) determined 10.8 ± 0.8 m.y. by ^{81}Kr. Measured

^{14}C activity of about 53.3 ± 0.4 dpm/kg. (Jull *et al.* 1997) is consistent with saturation (61 ± 9 dpm/kg). Pal *et al.* (1986) and Jull *et al.* (1999) reported data for ^{10}Be, ^{26}Al, ^{36}Cl and ^{14}C. Since we know that Nakhla has been on Earth for 100 years, this data helps interpret similar data for Lafayette and Governador Valadares.

Other Isotopes
Fallick *et al.* (1983), Kerridge (1988), Watson *et al.* (1994) and Leshin *et al.* (1996) have reported on the hydrogen isotopic composition of water released from Nakhla (figure 16). Hydrogen released at high temperatures is enriched in deuterium, but hydrogen released at low temperature has a terrestrial ratio.

Fallick *et al.* (1983), Carr *et al.* (1985), Wright *et al.* (1992), Sephton *et al.* (2000) and Jull *et al.* (2000) have reported on the isotopic composition of carbon extracted from Nakhla. Carr *et al.* argued that the heavy carbon ($\delta^{13}C$ = +12 to +24 ‰) may be from carbonates that are produced by weathering on Mars. The carbon and nitrogen content and isotopic composition has also been reported by Wright *et al.* (1992). Using leaching experiments to get rid of ^{14}C component, Jull *et al.*

Table 1a. Chemical Composition of Nakhla.

reference	Schmitt63	Haskin66	Weinke78	Treiman86	Dreibus82	McCarthy74	Prior 1912	Nakamura73 293 mg	Nakamura73 158 mg	Podosek73 (Laul72)
weight						8 g		293 mg	158 mg	
SiO2					49.33	48.24 (a)	48.97(b)			
TiO2					0.35	0.29 (a)	0.38 (b)			
Al2O3					1.64	1.45 (a)	1.74 (b)			
FeO					21.7	20.63 (a)	20.79 (b)			
MnO					0.55	0.54 (a)	0.09 (b)			
CaO					14.3	15.08 (a)	15.17(b)			13.71
MgO					11.82	12.47 (a)	12 (b)			
Na2O					0.566	0.42 (a)	0.4 (b)			
K2O					0.166	0.1 (a)	0.14 (b)			0.13
P2O5					0.103	0.12 (a)				
sum					100.5	99.34	99.68			
Li ppm					3.8					
Sc	53.6 (d)		78 (d)	46	55					
V					192.4					
Cr					1710	2900 (a)	2300 (b)			**Laul72**
Co					54					81 (e)
Ni				72	90					
Cu			18.3		6.7					5.03
Zn			64	55	220					42
Ga			3.4							2.7
Ge				2.97						
Se			0.09	0.064						
Br				4.55	4.08					4.37
Rb			4.75	5.01				3.15		2.8
Sr								51.4		
Y	3.17	4.4								
Zr										
Nb										
Mo				0.086						
Pd ppb				42						
Ag ppb				1380						40
Cd ppb				115						71
In ppb				14.6						24.4
Sn ppb			580							
Sb ppb			250	19	6					
Cs ppm			0.49	0.349						0.287
Ba					34			32.5	31.3	
La	1.57	1.6	1.14		2.14			2.24	2.28	
Ce	6.19	6.2	2.7	5.37	5.6			5.97	6.2	
Pr	0.67	0.67								
Nd	3.18	3.2	1.58	3.38	2.85			3.11	4.06	
Sm	0.73	0.73	0.5		0.78			0.815	0.855	
Eu	0.2	0.2	0.14	0.223	0.23			0.249	0.276	
Gd	0.94	0.04	0.62					0.796	0.84	
Tb	0.109	0.109	0.082	0.115	0.13					
Dy			0.52					0.723	0.808	
Ho	0.14	0.14	0.1		0.17					
Er	0.34	0.34						0.404	0.441	
Tm	0.047	0.057	0.038							
Yb	0.23	0.32	0.24	0.386	0.4			0.358	0.397	
Lu	0.044	0.051	0.029	0.0559	0.062			0.0535	0.0557	
Hf					0.29					
Ta					0.09					
W ppb					176					
Re ppb			<5	0.041						
Os ppb			1	0.2						
Ir ppb				0.153	<2					17
Au ppb			0.7	0.897	2.9	**Ehmann & Lovering67**				0.55
Hg ppb						230				
Tl ppb					3.8					3.1
Bi ppb		**Chen & Wasserburg 86**			5.4	**Morgan & Lovering73**				0.5
Th ppm	0.213 (c)					0.191			0.236	
U ppm	0.053 (c)				0.065	0.049			0.056	

technique: (a) XRF, (b) wet chem., (c) IDMS, (d) INAA, (e) RNAA

Table 1b. Composition of Nakhla (continued).

reference / weight	Lodders 98 averages	Schmidt 72 270 mg	Schmidt 72 742 mg	Schmidt 72 262 mg	Bunch 75 fusion crust	Mittlefehldt 97 56 mg	Kong 99 48 mg	Wang 98	Dreibus 03 El.G	Dreibus 03 Grady
SiO2	48.6				47.9 (g)					
TiO2	0.34				0.3 (g)		0.37 (d)			
Al2O3	1.68				1.57 (g)		1.98 (d)			
FeO	20.6	21.1 (d)	23.16 (d)		18.5 (g)	20.7 (d)	17.5 (d)		16.08	19.54
MnO	0.49	0.48 (d)	0.45 (d)	0.47 (d)	0.5 (g)		0.56 (d)			
CaO	14.7				15.4 (g)	15.1 (d)	19.45 (d)		14.7	14.4
MgO	12.1				11.8 (g)		12.02 (d)			
Na2O	0.46	0.51 (d)	0.41 (d)	0.52 (d)	0.4 (g)	0.446 (d)	0.55 (d)		0.729	0.574
K2O	0.13				0.04 (g)	0.1 (d)	0.16 (d)			
P2O5	0.13									
sum										
Li ppm	3.9									
Sc	51	53 (d)	47 (d)			57.2 (d)	64.2 (d)		56.1	55.5
V	192						251 (d)			
Cr	1770	1820 (d)	1580 (d)				2050 (d)			
Co	48	43 (d)	47 (d)			49.8 (d)	43.9 (d)	26.9 (e)	36.9	44.8
Ni	90					70 (d)	77.1 (d)		58	60
Cu	12	15 (d)	14 (d)							
Zn	54					89 (d)	92.2 (d)	67.1 (e)	<70	70
Ga	3						8.82 (d)	2.92 (e)	3.7	3.4
Ge	3									
Se	0.08							0.0478 (e)		
Br	4.5	**Pinson 65**		**Gale 75**		3.2 (d)			3.46	8.45
Rb	3.8	2.63 (c)	2.95 (c)	3.9 (c)	4.74 (c)	(d)		2.93 (e)	<4	<7
Sr	59	59.82 (c)	59.4 (c)	66.4 (c)	64.3 (c)	70 (d)			65	90
Y	3.3									
Mo	0.086						0.137 (e)			
Ag ppb	40						246 (e)	32.1 (e)		
Cd ppb	93							96.6 (e)		
In ppb	20							20.2 (e)		
Sb ppb	40							4.6 (e)		
Te ppb	<4.3							6.7 (e)		
Cs ppm	0.39					0.38 (d)		1.11 (e)	0.26	0.6
Ba	29					20 (d)			40	31
La	2.06					1.48 (d)	2.52 (d)		2.18	2.39
Ce	5.87					4.3 (d)	2.59 (d)		5.35	6.8
Pr	0.67									
Nd	3.23								2.93	3.4
Sm	0.77					0.68 (d)	1.11 (d)		0.867	0.862
Eu	0.235					0.207 (d)	0.321 (d)		0.236	0.26
Gd	0.86						2.21 (d)			
Tb	0.12					0.12 (d)	0.208 (d)		0.14	0.16
Dy	0.77								0.9	0.99
Ho	0.155								0.18	0.16
Er	0.37									
Tm	0.047									
Yb	0.39					0.33 (d)	0.512 (d)		0.35	0.37
Lu	0.055	**Lee & Halliday 97**				0.055 (d)	0.085 (d)		0.052	0.061
Hf	0.27	0.204 (c)	0.1641 (c)			0.24 (d)	0.34 (d)		0.31	0.28
Ta	0.09					0.065 (d)				
W ppb	120	264.1 (c)	297.6 (c)	**Birk & Allegre 94**			145 (e)	**Brandon 00**	170	320
Re ppb	0.036			0.0338 (c)	0.0323 (c)			0.052 (f)		
Os ppb	0.007			0.00951 (c)	0.004 (c)		0.38 (e)	0.0137 (f)		
Pt ppb	0.5						17.2 (e)			
Ir ppb	0.22						4.35 (e)			
Au ppb	0.72						1.05 (e)	1.21 (e)	0.0075	0.0005
Tl ppb	3.5							2.02 (e)		
Bi ppb								3.44 (e)		
Th ppm	0.198					0.1 (d)			0.17	0.2
U ppm	0.052							0.0373 (e)	<0.06	0.044

technique (c) IDMS, (d) INAA, (e) RNAA, (f) IDMS, (g) elec. Probe
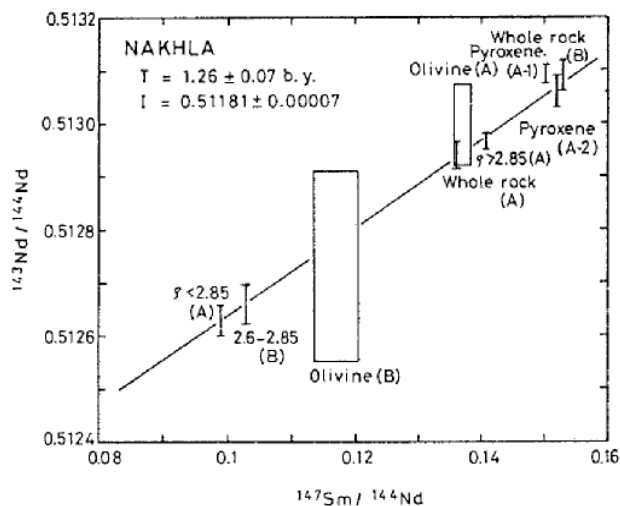
Figure 13. Sm-Nd isochron for Nakhla determined by Nakamura et al. (1982).

Figure 14. U-Pb concordia diagram for mineral separates from Nakhla. This is figure 4 in paper by Nakamura et al. (1982) GCA **46**, 1563.

(1995) found that the $\delta^{13}C$ for some of the carbon in Nakhla was as heavy as + 35‰. However, in a more recent study by Jull *et al.* (2000), $\delta^{13}C$ was found to be as low a - 33 ‰ in the hot-acid-labile extracts (*see section on Evidence of Biological Activity*). Grady *et al.* (1995b) reconsidered the data of Carr *et al.* for ^{13}C after acid dissolution experiments and concluded that very heavy carbon $\delta^{13}C = +50$ ‰) of Martian origin was present. This value is similar to the isotopic ratio of carbon in the carbonate in ALH84001, and seems to verify the conclusions by Reid and Bunch (1975), Carr *et al.* (1985) and Gooding *et al.* (1991), that the weathering in Nakhla occurred on Mars, not during the time it has been on Earth.

Mathew and Marti (2002) determined nitrogen isotopes along with rare gas component as a function of temperature release. The heavy nitrogen found at very high temperatures is due to spallation.

Taylor *et al.* (1965) found that the ratio of oxygen isotopes in pyroxenes from Nakhla were similar to those in Shergotty and different from those in howardites and eucrites. Clayton and Mayeda (1983, 1996) and Franchi *et al.* (1999) reported the oxygen isotopes for Nakhla. Clayton (1993) reported the $^{18}O/^{16}O$ composition of olivine and pyroxene from Nakhla. Karlsson *et al.* (1992) found that the oxygen isotopes in water released from Nakhla and other Martian meteorites was enriched in ^{17}O, suggesting that the past hydrosphere on Mars was from a different reservoir than the lithosphere. Baker *et al.* (1998) have determined the isotopic composition of oxygen in water
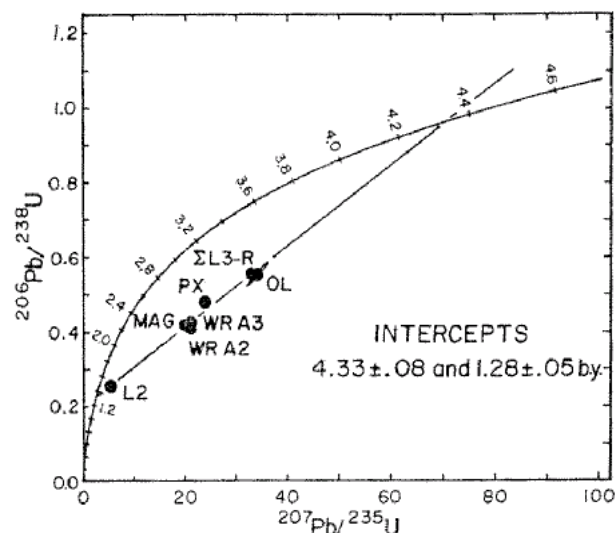
released during heating of Nakhla. Saxton *et al.* (1997, 1998) reported $\delta^{18}O = 34 \pm 1$ ‰ for 4 grains of siderite - which makes it the heaviest Martian carbonate!!

Farquhar *et al.* (2000) and Greenwood *et al.* (2000) have studied the sulfur isotopes. Farquhar *et al.* have reported a significant $\Delta^{33}S$ anomaly in Nakhla. However, Greenwood *et al.* did not find the anomaly in pyrrhotite (igneous origin), so that the $\Delta^{33}S$ anomaly must be in the added salts recording an isotopically anomalous atmospheric component.

Molini-Velsko *et al.* (1986) found that the isotopic composition of Si was normal.

Ott and Begemann (1985) originally showed that there was excess ^{129}Xe in Nakhla. Musselwhite *et al.* (1991), Drake *et al.* (1993, 1994) and Swindle (1995) discussed the origin of this excess and originally argued for an ancient Martian hydro-alteration effect. Turner *et al.* (1996) reported excess ^{129}Xe within Nakhla pyroxene and Ott *et al.* (1988) found that the Xe in carefully etched "residue" from Nakhla was like that of Chassigny. Gilmour *et al.* (1997, 1998) and Mathew *et al.* (1998, 1999, 2001) have continued these studies on mineral separates in order to determine the exact siting of Xe in Nakhla. Gilmour *et al.* (2001) conclude that Nakhla contains two Xe components: one associated with a water-soluble phase enriched in ^{129}Xe and associated with the Martian atmosphere (shock implantation?) and the other a mixture of Martian interior Xe with some spallation Xe. Bart *et al.* (2001) also
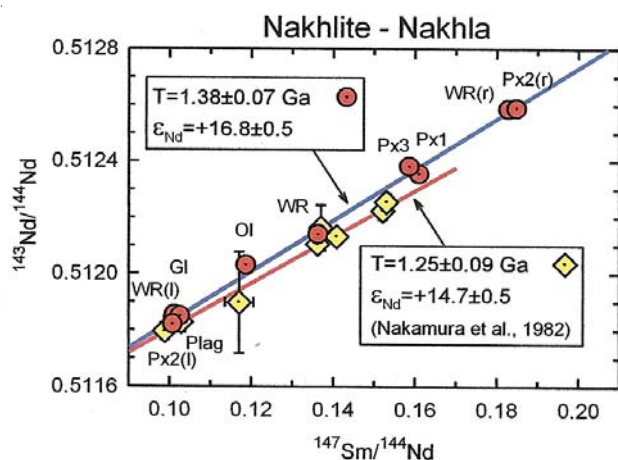
Figure 15. *Internal mineral diagram for Sm-Nd isotope system (Shih et al. 2010).*

conclude that the [129]Xe-enriched component is due to "shock implantation" of Martian atmosphere. Mathew and Marti (2002) found that the Xe component released at high temperature (>1000ºC) contained evidence that Mars has effectively retained [244]Pu-derived fission gas.

Harper *et al.* (1995) reported a small but significant excess of [142]Nd in Nakhla. According to Harper *et al.*, *"This anomaly records differentiation in the Martian mantle before 4539 million years ago and implies that Mars experienced no giant impacts at any time later than 27 million years after the origin of the solar system."* This isotopic anomaly has now also been observed in Chassigny by Jagoutz (1996). Lee and Halliday (1997) also reported excess [182]W in Nakhla.

Birck and Allègre (1994) and Brandon *et al.* (2000) have studied the Re-Os isotopic systematics of Nakhla. The Os isotopic composition was found to be radiogenic. From the Re/Os fractionation Birck and Allègre concluded the mantle of Mars has a relatively high oxidation state! Brandon *et al.* noted that it was further evidence that the Martian mantle wasn't well mixed Smith *et al.* (1983) showed that the relatively high Ni content of olivine and pyroxene in nakhlites also indicated relatively oxidizing conditions. The presence of magnetite also is proof of this.

Hutchison *et al.* (1975), Nakamura *et al.* (1982), Chen and Wasserburg (1986b), Jagoutz *et al.* (2001) and Bouvier et al. (2005) have studied the U-Th-Pb isotopic system for Nakhla. Chen and Wasserburg discussed the problem of *"terrestrial Pb"* contamination. In fact,

one must now also consider contamination by *"Martian Pb"* during the alteration process that has been shown to have occurred on Mars (Gooding 1991).

Miscellaneous Studies

Bhandari *et al.* (1971) reported track evidence for superheavy elements in diopside from Nakhla and this led to a rash of studies (Carver and Anders 1976; Green *et al.* 1978; Crozaz 1979). However, it turned out that the long, etched tracks in Nakhla observed by Bhandari are a shock-related feature and not due to the presence of extinct "superheavy" elements *(i. e. Nakhla is too young (1.3 b.y.) to have incorporated short-lived superheavy elements).*

Kaneda *et al.* (1997) and McKay *et al.* (1993, 1994) have performed experiments to determine trace element partioning between pyroxene and synthetic melts.

Harvey and McSween (1992), Treiman (1993), Varela *et al.* (1999), Stockstill *et al.* (2005) and Sautter et al. (2012) studied the melt inclusions in augite to obtain the composition of the parental magma.

McFadden et al. (1987), Hamilton *et al.* (1997), McHone et al. (1999), Schade and Walsch (1999) and Ueda et al. (2002) obtained spectra of Nakhla.

The magnetic properties of Nakhla have recently been investigated by Shaw *et al.* (2001) who report a Martian magnetic field of 4 ìT as recently as 1.3 b.y. The magnetic phase in Nakhla appears to be titanomagnetite (Collinson 1997; Rochette *et al.* 2001).

"Evidence for Biological Activity"

Toporski *et al.* (1999, 2000) have shown that Nakhla is contaminated through to the center with both cellular structures and what appears to be *"exopolymeric secretions"*. They claim that in some cases the organisms are apparently still growing! Glavin *et al.* (1999) showed that Nakhla has the same amino acid profile as the sediment it was removed from *(which must have a wealth of microbial life).* Sephton *et al.* (2000) have used careful GCMS to study the "aromatic high molecular weight organic matter" extracted from Nakhla samples that were thought to be "pristine". Their analyses are consistent with Jull *et al.* (2000) who conclude that as much as 75% of the organic matter in Nakhla *"may not be recent terrestrial contamination"*. D. McKay *et al.* (1999) and Gibson *et al.* (2000) illustrate *"spherical structures"* within,
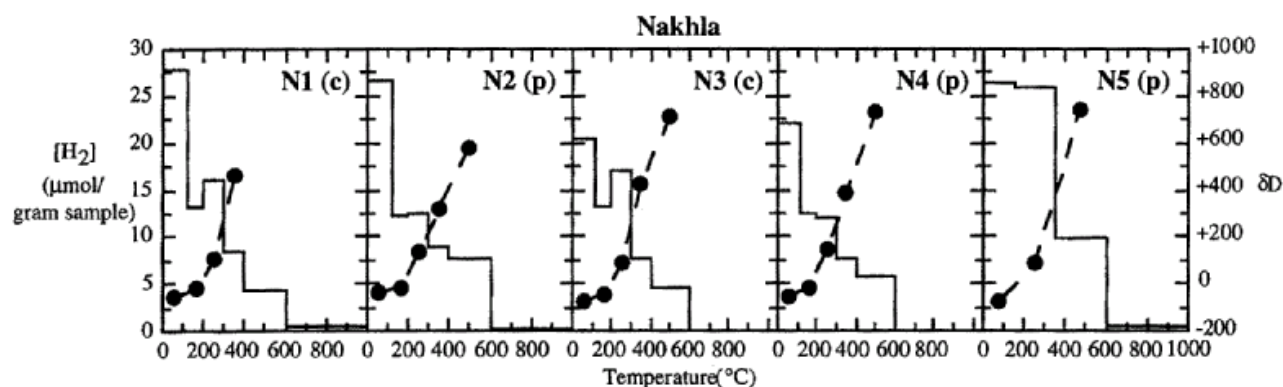
Figure 16. *Hydrogen isotopic composition of water relased from the Nakhla meteorite during pyrolysis (p) and combustion (c) experiments by Leshin et al. (1996).*

or beneath, "*iddingsite*" alteration in Nakhla. Flynn *et al.* (1999) studied the organic carbon in Nakhla at high spatial resolution *(but could not rule out terrestrial contamination).*

Processing
Although Nakhla is considered as one meteorite, it arrived as a shower of many pieces (~40), most apparently with fusion crusts (*see Introduction*). In general, it is not known from which pieces the main research has been done, or if all pieces are the same. Note that Friedman *et al.* (1994) have been looking at thin sections of different portions of Nakhla to see what variability may exist (Lentz *et al.* 2001).

The ~40 pieces of Nakhla have been widely distributed and often traded (figure 17). In 1955, the Cairo Museum had individual specimens weighing 1813 g, 1651 g, 1318 g, 431 g, 393 g, 29 g and 20 g (Attia *et al.* 1955). In 1985, Graham *et al.* list specimens as follows (British Museum 667+ 9 g, 641 g, 313 g, 156+ 14 g and 110 g; Smithsonian 644 g; Berlin 602 g; Vienna 500 g; Paris 430 g; Harvard 159 g). Additional samples that are known include: 123 grams at the Research School of Earth Science in Canberra, 80 grams in Russia, 78 grams at UCLA, 67 grams in Perth, 50 grams in Dublin, 28 grams in Ottawa, 34 grams in Tempe, 23 grams in Prague and 8 grams at Mainz. Note that the actual weight collected was only about 10 kg (Attia *et al.* 1955; Grady 2001). Please check the meteorite database (Metbase) maintained by Joern Koblitz (University of Bremen) for current distribution.

Thin sections of the Nakhla meteorite are included in the educational thin section sets distributed by the British Museum of Natural History (Grady and Hutchison 1996). One set of 23 consecutive thin sections is

available from the Smithsonian Institution (USNM). *(Note that, in order to study salts in Nakhla, it is important not to use polar solvents (H_2O) during processing nor thin section preparation).*

In July 1998, a large piece (640 grams) of Nakhla from the British Museum (BM1913,25), was split in a dry nitrogen glove box at JSC and processed for distribution to a large number of scientists under the direction of Monica Grady (figures 18, 19, 20). Before splitting in 1998, it was completely covered with fusion crust *(however, if it was entered into the BM collection in 1913, it may have been on the ground in the area of the Nile delta, for one or two years).* Knowledge of the exact history of the sample is important for studies of the salts and organics.

Mathew and Marti (2002) report that the piece of Nakhla they obtained from the British Museum was Nakhla C, but, in general, scientists do not give enough information about the exact piece they studied (*sigh, moan and grown*).

It is not known, which samples of Nakhla have been washed, sawn using water or kerosene, or exposed to contamination. This information is needed in order to properly interpret the results of the studies of "salts" and "organics" in these samples from Mars.
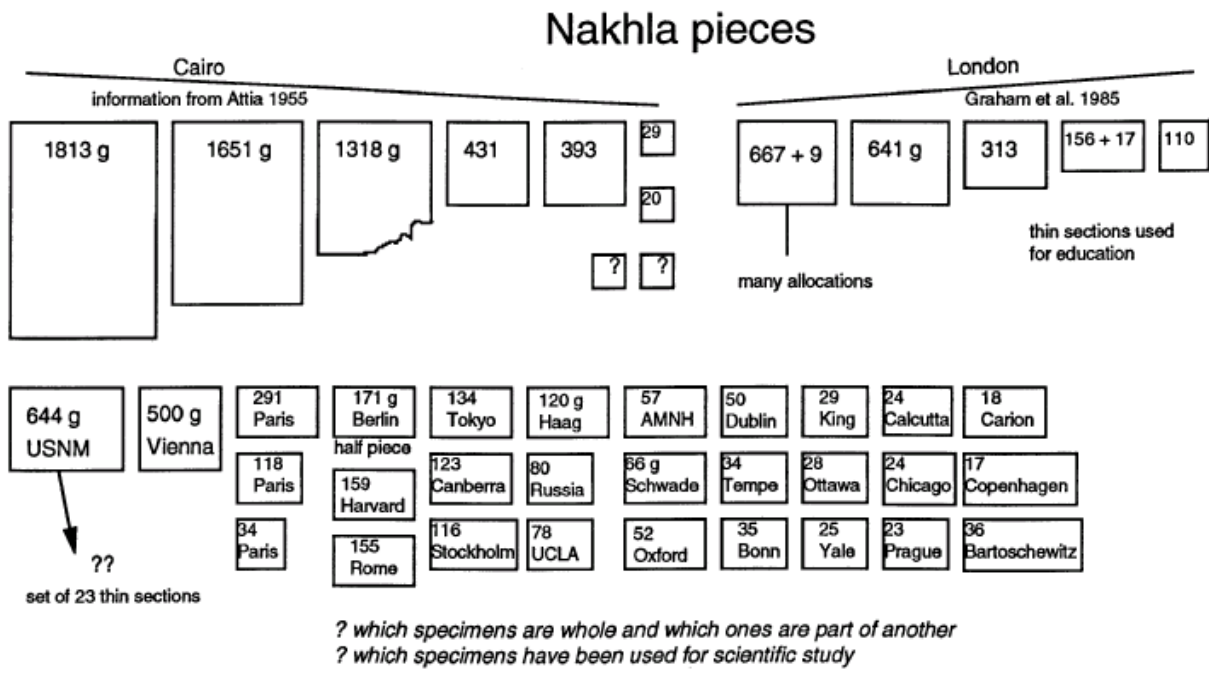
References for Nakhla

Nakhla pieces

Cairo
information from Attia 1955

| 1813 g | 1651 g | 1318 g | 431 | 393 | 29 |

20

? ?

London
Graham et al. 1985

| 667 + 9 | 641 g | 313 | 156 + 17 | 110 |

thin sections used
for education

many allocations

644 g USNM | 500 g Vienna

??

set of 23 thin sections

291 Paris	171 g Berlin (half piece)	134 Tokyo	120 g Haag	57 AMNH	50 Dublin	29 King	24 Calcutta	18 Carion
118 Paris	159 Harvard	123 Canberra	80 Russia	66 g Schwade	34 Tempe	28 Ottawa	24 Chicago	17 Copenhagen
34 Paris	155 Rome	116 Stockholm	78 UCLA	52 Oxford	35 Bonn	25 Yale	23 Prague	36 Bartoschewitz

? which specimens are whole and which ones are part of another
? which specimens have been used for scientific study

Figure 17. *Schematic drawing showing locations of pieces of Nakhla meteorite in 1996.*

Nakhla from British Museum
(completely covered with fusion crust)

Whole Piece
637 grams

split at JSC July 1998

Half
291 g.

Half
346 g.

allocations July 1998

Grady Consortium
,1 - ,50

Jull et al, 2000
Bridges and Grady
1999, 2000

,66
38 g.

,69
17 g.

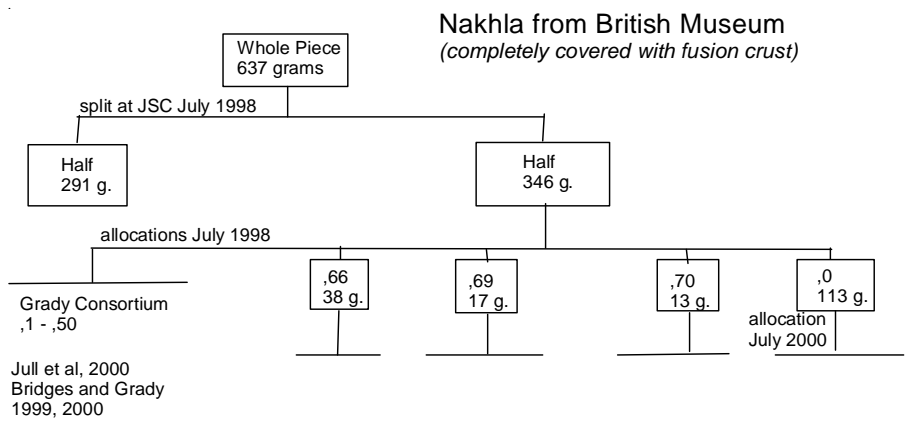,70
13 g.

,0
113 g.

allocation
July 2000

Figure 18. *Recent processing at JSC of Nakhla 1913,25 from the the British Museum (see Monica Grady for detail).*
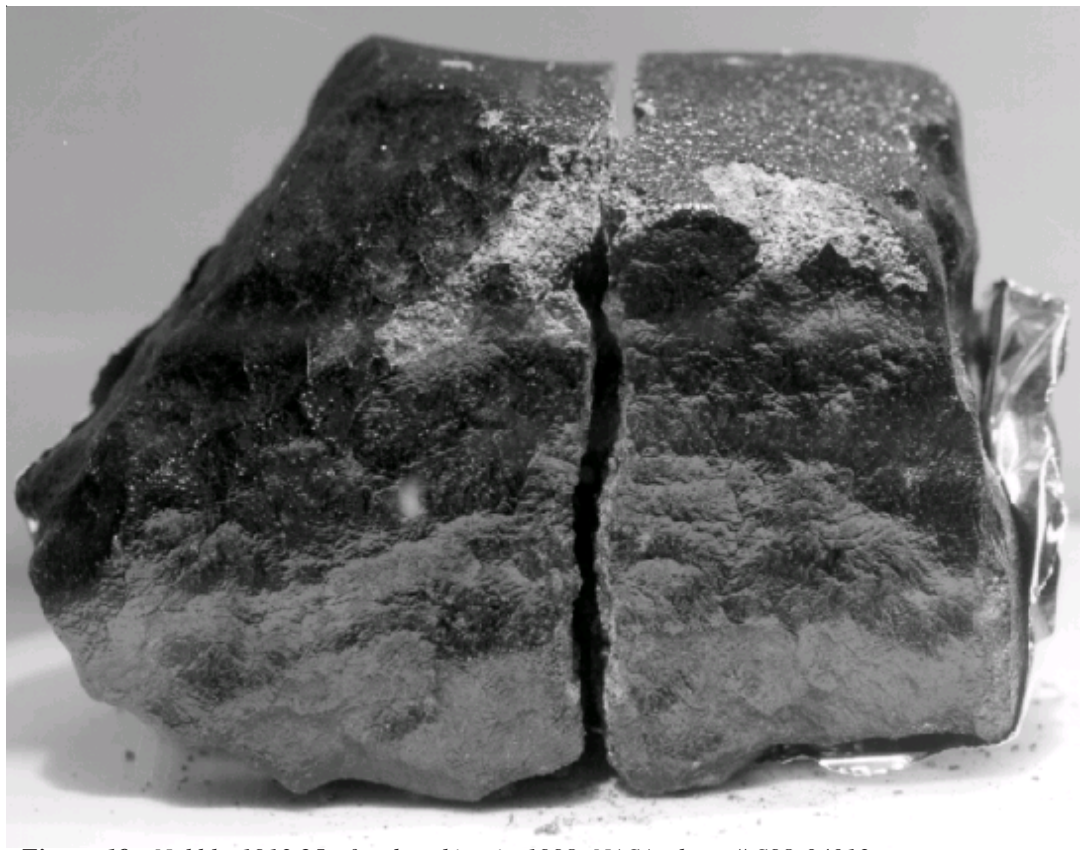
Figure 19. *Nakhla 1913,25 after breaking in 1998. NASA photo # S98-04013*

Figure 20. *Nakhla 1913,25 (inside surfaces) after breaking in 1998. NASA photo # S98-04014*