III. Lafayette

Clinopyroxenite, 800 grams

fresh

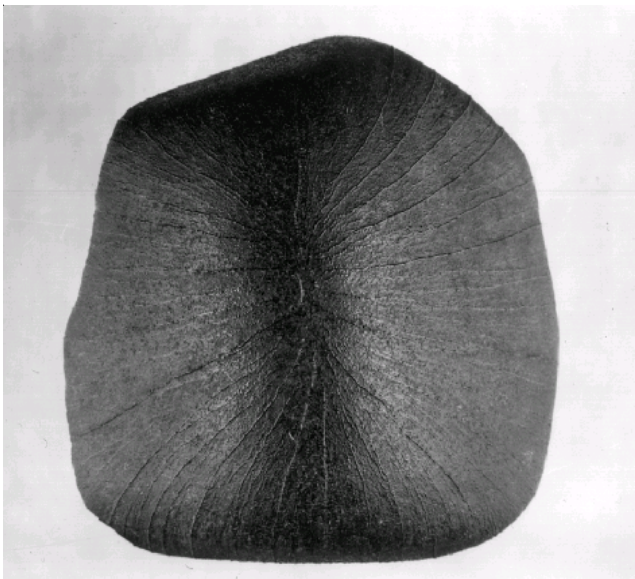

Figure III-1. *Photograph showing fine ablation features of fusion crust on Lafayette meteorite. Sample is shaped like a truncated cone. This is a view of the top of the cone. Sample is 4-5 centimeters across. Photograph from Field Museum Natural History, Chicago, number 62913.*

Figure III-2. *Photograph of bottom surface of Lafayette meteorite. Photograph from Field Museum Natural History, Chicago, number 62918.*

Figure III-3. *Side view of Lafayette. Photograph from Field Museum Natural History, Chicago, number 62917.*

Introduction

According to Graham *et al.* (1985), *"a mass of about 800 grams was noticed by Farrington in 1931 in the geological collections in Purdue University in Lafayette Indiana."* It was first described by Nininger (1935) and Mason (1962). Lafayette is very similar to the Nakhla and Governador Valadares meteorites, but apparently distinct from them (Berkley *et al.* 1980). Lafayette is a single stone with a fusion crust showing well-developed flow features from ablation in the Earth's atmosphere (figures III-1,2,3). The specimen is shaped like a rounded cone with a blunt bottom end. It was apparently oriented during entry into the Earth's atmosphere. Note that the fine ablation features seen on Lafayette have not been reported on any of the Nakhla specimens.

Karlsson *et al.* (1992) found that Lafayette contained the most extra-terrestrial water of any Martian meteorite and Treiman *et al.* (1993) reported that it contained the most alteration material. Kerridge (1988), Watson *et al.* (1994) and Leshin *et al*. (1996) found that the water released during stepwise heating of Lafayette was enriched in deuterium.

Petrography

The petrography of the Lafayette meteorite has been described by Bunch and Reid (1975), Reid and Bunch (1975), Boctor *et al.* (1976), Berkley *et al.* (1980), Harvey and McSween (1992b) and Treiman *et al.* (1993). Treiman *et al.* (1993) describe Lafayette as a cumulate clinopyroxenite where the cumulus material

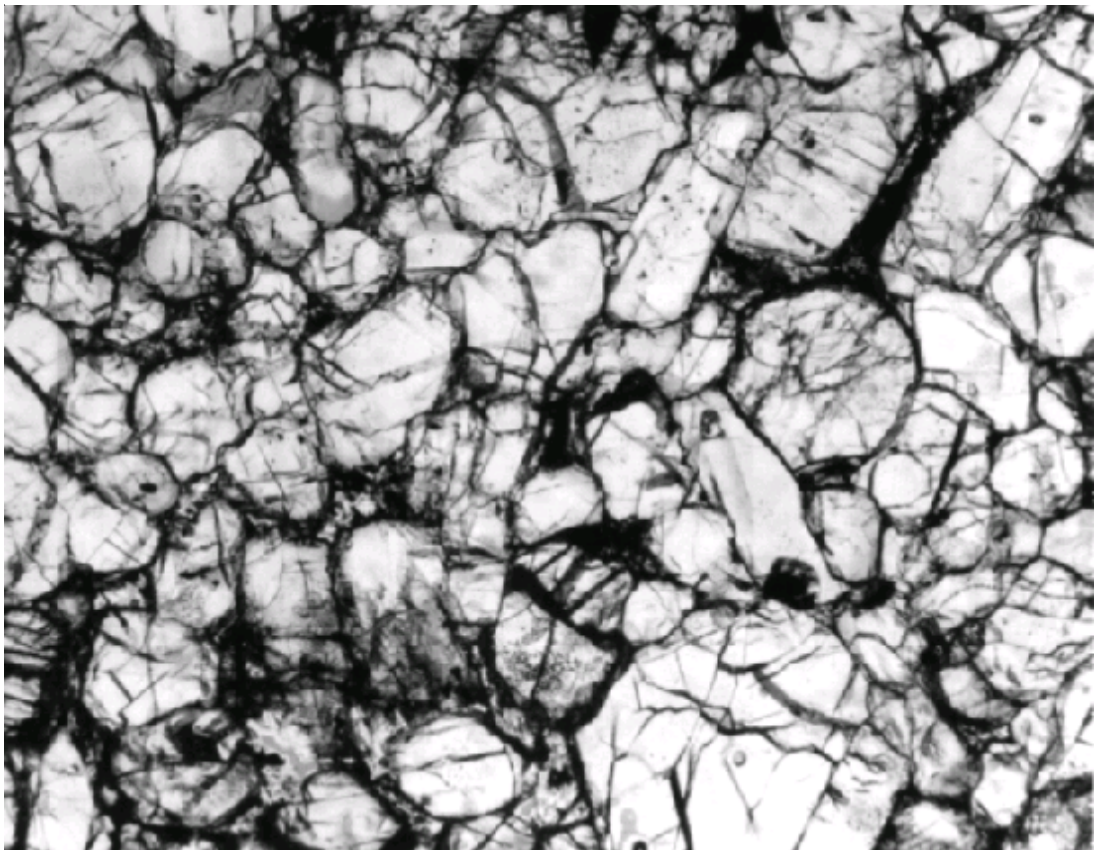

Figure III-4. *Photomicrograph of thin section of Lafayette meteorite. Field of view 2.2 mm. Sample #1505-3 from the Smithsonian.*

is represented as subhedral augite and olivine grains (figure III-4). The elongate pyroxenes in the nakhlites are weekly aligned (Berkley *et al.* 1980). Among the cumulus grains is intercumulus material (mesostasis) consisting of plagioclase, orthopyroxene, pigeonite, alkali feldspar, Ti-magnetite, ilmenite, pyrite, silica-glass and minor phases.

Two pyroxene geothermometry for Lafayette indicates temperatures around 950°C, suggesting subsolidus equilibration (Harvey and McSween 1992b). However, the Fe/Mg ratio of the olivine shows that it is out of equilibrium with the pyroxene.

Post-magmatic hydrous alteration material is apparent in hand-specimen and thin section as rusty red-orange to black veins, staining and intergranular films (Treiman *et al.* 1993). Olivine is the most altered, but similar staining occurs in pyroxene and throughout the sample (figure III-5).

The Lafayette meteorite has been altered in a saline solution, as was Nakhla (Vicenzi and Eiler 1998; Greenwood *et al.* 1998; Bridges and Grady 2000) *(see section on "Extra-terrestrial Weathering").*

Mineral Chemistry

***Olivine*:** As is the case for Nakhla, the olivine (Fo_{35}) in Lafayette has higher Fe/Mg than that of coexisting pyroxene. A careful study of olivine zoning by Harvey and McSween (1992b) noted that olivine in Lafayette has relatively homogeneous Fe, Mg composition, indicating that it re-equilibrated with the intercumulus liquid during cooling. Lentz *et al.* (1999) also give analyses of olivine. Smith *et al*. (1983) determined high Ni and Ca contents in olivine from Lafayette.

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

Olivine	16.6%	18.6	7.4	20
Pyroxene	74.4	70.4	84	69.3
Mesostasis	9	11	8.6	10.7

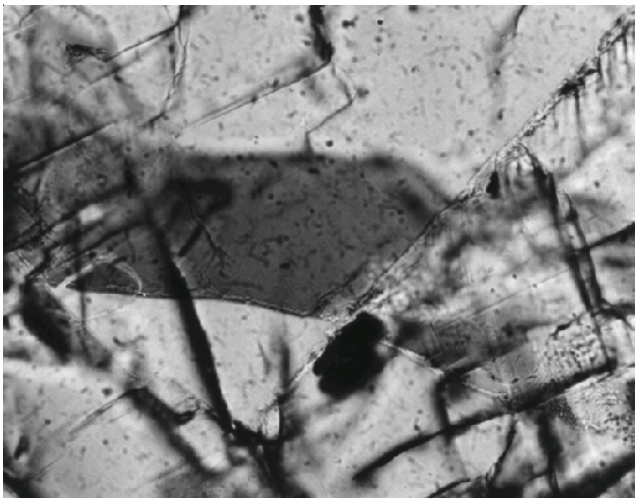

Figure III-5. *Photomicrograph of thin section of Lafayette showing "iddingsite" alteration along a fracture in olivine.*

However, Mikouchi and Miyamoto (1997) noted that the trace Ca contents of olivine in Lafayette (~0.2%) was less than that in olivine from Nakhla or Governador Valadares (~0.5%).

***Orthopyroxene*:** Lafayette has poikilitic grains of orthopyroxene that formed from reaction of olivine with an evolving intercumulus liquid (Harvey and McSween 1992b). The orthopyroxene is homogeneous in composition. Orthopyroxene is a minor component, however.

***Clinopyroxene*:** The major mineral is augite ($En_{39}Fs_{22}Wo_{39}$) with little compositional zoning (Boctor *et al.* 1976; Harvey and McSween 1992b; Lentz *et al.* 1999) (figure III-6). Mikouchi and Miyamoto (1997) found that the composition of pyroxene overgrowth in Lafayette is more Mg-rich and Ca-poor than in Nakhla or Governador Valadares. Lentz *et al.* (2002) reported that Li, Be and B increased in concentration from pyroxene core to rim.

***Plagioclase*:** Bunch and Reid (1975) give the composition of plagioclase as $An_{32}Ab_{65}Or_{6}$. Lentz *et al.* (2002) determined Li, Be and B in plagioclase.

***K-feldspar*:** Potassium feldspar is found in the mesostasis ($Or_{76}Ab_{21}An_{3}$).

***Iddingsite*:** Reid and Bunch (1975) noted the fibrous habit of the alteration in Nakhla and Lafayette and reasoned that it might be *"pre-terrestrial, low temperature, alteration."* Iddingsite is a fine-grained intergrowth of smectite clay, ferrihydrite and ionic salt

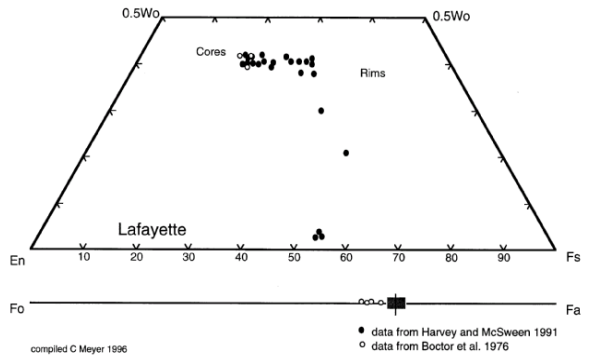

Figure III-6. *Pyroxene and olivine composition diagram for Lafayette meteorite. Data compiled from Boctor et al. (1976) and Harvey and McSween (1991).*

minerals (Boctor *et al*. (1976), Treiman *et al*. (1993), Romanek *et al.* (1996) and Treiman and Lindstrom (1997). In particular, Treiman *et al.* showed that the smectite alteration products were indeed formed in a pre-terrestrial environment (*i.e*. on Mars!). Iddingsite is more abundant in Lafayette than in Nakhla (Karlsson *et al.* 1992; Treiman *et al.* 1993; Romanek *et al.* 1996; Bunch and Reid, 1975)*(see also "Oxygen Isotopes" below*). Treiman and Lindstrom (1997), Bridges and Grady (2000) and Newsom *et al*. (2001) have analyzed iddingsite from Lafayette (table III-2). Vincenzi and Eiler (1998) obtained high spatial resolution chemical imaging of the veinlets of "iddingsite" and noted distinct mineral phases with intricate banding. Ar age dating and Xe, Kr isotopic analysis of iddingsite are consistent with alteration on Mars (Swindle *et al*. 2000). Similar alteration in Y000749, has been reported by Treiman and Goodrich (2002).

Cl-apatite: Crozaz (1979) studied the U and Th distribution in Lafayette and determined the Th/U ratio in small grains (30 microns) of Cl-apatite. Bunch and Reid (1975) reported fluor-chlorapatite (Cl=4%, F=1.6%). Bridges and Grady (2000) give a trace element analyses of Cl-apatite.

***Titaniferous magnetite*:** Ti-rich magnetite in Lafayette has exsolved ilmenite lamellae (Boctor *et al.* 1976). See also photomicrograph and analysis in Bunch and Reid (1975).

***Glass*:** Interstitial glass has been analyzed by Berkley *et al*. (1980).

***Sulfides*:** Bunch and Reid (1975) reported both troilite and "stoichiometric" pyrite. The composition of pyrite

Table III-1a. Chemical composition of Lafayette.

reference	Schmitt63		Haskin66		Laul72		Schmitt72		Boctor76		Podesek73	Treiman86	Nichiporuk67	
weight							889 mg		fusion crust					
SiO2									46.9	(d)				
TiO2									0.33	(d)				
Al2O3									1.55	(d)				
FeO							23.03	(a)	22.7	(d)				
MnO							0.5	(a)	0.79	(d)			0.39	(f)
CaO									13.4	(d)	14.13		9.08	(f)
MgO									12.9	(d)				
Na2O							0.43	(a)	0.36	(d)				
K2O	0.12	(a)							0.09	(d)	0.113			
P2O5														
sum														
Li ppm														
Sc	77.6	(a)	54	(a)			48	(a)						
V														
Cr							1720	(a)						
Co							44	(a)					37	(f)
Ni												94	106	(f)
Cu							12	(a)						
Zn					71	(b)						72		
Ga														
Ge												2.48		
As														
Se					0.088	(b)						0.05		
Br												0.17		
Rb					2.4	(b)						3.25		
Sr														
Y	4.4	(a)	3.2	(a)										
Zr														
Nb														
Mo														
Pd ppb												<1.7		
Ag ppb					58	(b)								
Cd ppb					92	(b)						98		
In ppb					20.3	(b)						20.1		
Sb ppb												103		
Te ppb												<5.2		
I ppm														
Cs ppm					0.288	(b)						0.353		
Ba														
La	1.76	(a)	1.8	(a)										
Ce	5.48	(a)	5.5	(a)								4.21		
Pr	0.8	(a)	0.8	(a)										
Nd	3.35	(a)	3.4	(a)								3.12		
Sm	0.85	(a)	0.85	(a)										
Eu	0.24	(a)	0.24	(a)								0.188		
Gd	0.92	(a)	0.92	(a)										
Tb	0.12	(a)	0.12	(a)								0.104		
Dy	0.89	(a)	0.89	(a)										
Ho	0.146	(a)	0.146	(a)										
Er	0.4	(a)	0.4	(a)										
Tm	0.057	(a)	0.047	(a)										
Yb	0.36	(a)	0.22	(a)								0.307		
Lu	0.051	(a)	0.044	(a)								0.055		
Hf														
Ta														
W ppb														
Re ppb												0.028		
Os ppb												<0.6		
Ir ppb					0.13	(b)						0.052		
Au ppb					21	(b)						66.2		
Tl ppb					7.2	(b)						6.81		
Bi ppb					5.64	(b)						5		
Th ppm														
U ppm												0.044		

technique: (a) INAA, (b) RNAA, (c) IDMS, (d) elec. Probe, (e) XRF, (f) emission spec.

Table III-1b. Composition of Lafayette (continued).

reference	Mittlefehldt 97		Wang 98		*Lodders 98*	Dreibus 03
weight	40 mg				*averages*	
SiO2					*46.9*	
TiO2					*0.42*	
Al2O3					*2.47*	
FeO	21.9	(a)			*21.6*	20.13
MnO					*0.5*	0.515
CaO	14.3	(a)			*13.4*	13.2
MgO					*12.9*	
Na2O	0.497	(a)			*0.4*	0.427
K2O					*0.11*	
P2O5					*0.45*	
sum					***99.15***	
Li ppm						3.9
Cl					*65*	101
Sc	53.6	(a)			*58*	51.1
V					*169*	
Cr					*1280*	
Co			29	(b)	*43*	45.4
Ni					*96*	90
Cu					*12*	
Zn			70.9	(b)	*78*	79
Ga			3.3	(b)	*3*	3.5
Ge					*2.5*	
As					*<150*	
Se			0.072	(b)	*0.07*	
Br					*0.37*	0.59
Rb			2.06	(b)	*2.8*	3.3
Sr					*75*	80
Y					*4.4*	
Zr					*9.4*	
Nb					*1.46*	
Mo						
Pd ppb					*1.7*	
Ag ppb			17	(b)	*58*	
Cd ppb			83.4	(b)	*95*	
In ppb			21.5	(b)	*20*	
Sb ppb			12	(b)		
Te ppb			3.1	(b)	*<5.2*	
Cs ppm			0.148	(b)	*320*	0.32
Ba					*27*	23
La					*1.86*	2
Ce	5.6	(a)			*4.82*	5.27
Pr					*0.8*	
Nd					*3.09*	3.2
Sm	0.83	(a)			*0.84*	0.794
Eu	0.25	(a)			*0.22*	0.238
Gd					*0.92*	
Tb	0.13	(a)			*0.12*	0.12
Dy					*0.95*	0.93
Ho					*0.17*	0.2
Er					*0.4*	
Tm					*0.057*	
Yb	0.39	(a)			*0.33*	0.445
Lu	0.056	(a)	**Lee 97**		*0.052*	0.059
Hf	0.34	(a)	0.2801	(c)	*0.28*	0.27
Ta	0.1	(a)			*80*	0.098
W ppb			151.2	(c)	*400*	200
Re ppb					*0.03*	
Os ppb					*0.6*	
Ir ppb					*0.09*	
Au ppb	2.9	(a)	2.85	(b)		3.4
Tl ppb			4.74	(b)	*7*	
Bi ppb			1.1	(b)	*5.3*	
Th ppm	0.21	(a)			*0.15*	0.19
U ppm			0.0653	(b)	*0.046*	0.043

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

Table III-2. Iddingsite (may be mixtures).

reference	Bunch 75	Bunch 75	Boctor 76	Treiman 93	Treiman 97	Gillet 2002	Gooding 91	Treiman 2002	
rock	Lafayette	Nakhla	Lafayette	Lafayette	Lafayette	NWA817	Nakhla	Y000749	
SiO2	42.9	43.6	43.7	49.1		46.51	40.2	49.08	52.24
TiO2			<0.01	0.01		0.03	0.2	0.02	0.03
Al2O3	5.5	5.8	4.29	4.77		2.26	0.74	3.49	3.12
FeO	28.2	27.5	26.8	29.01	29	28.42	34.1	28.75	30.03
MnO	0.28	0.37		0.48		0.28	0.63	0.15	0.31
CaO	0.65	0.73	1.35	0.7	2	0.14	1.14	0.45	0.46
MgO	8.7	9.4	10.2	13.9		7.56	6.82	7.49	3.99
Na2O	0.13	0.21	0.17	0.3	0.3	0.06	1.16	0.13	0.11
K2O	0.8	1.1	0.82	0.41	0.7	0.42	0.6	0.55	0.29
P2O5				0.09			0.06	0.15	0.26
sum	**87.16**			**98.77**		**86**	**85.65**	**90.26**	**90.84**
Sc ppm					0.4				
Cr					5				
Co					55				
Zn					160				
As					1				
Br					9				
Rb					40				
Sr					250				
Cs					20				
Ba					150				
La					<0.1				
Ce					<1				
Sm					0.04				
Eu					<0.2				
Tb					<0.2				
Yb					<0.2				
Lu					<0.03				
Hf					<0.3				
W ppb					1000				
Ir ppb					<8				
Au ppb					<8				
Th ppm					<0.2				

is given in Boctor *et al*. (1976). Two small grains of chalcopyrite were reported by Bunch and Reid (1975) (Cu=33%). Greenwood *et al*. (1998) report that marcasite is the main sulfide now found in Lafayette.

Carbonate: Vicenzi and Eiler (1998) have found that fine veinlets of siderite in Lafayette have the same heavy isotopic ratio as those in Nakhla. Bridges and Grady (2000) report that the siderite in Lafayette is 35% calcite and 6.5% rhodochrosite. They also give trace-element analyses for 5 siderite grains from Lafayette.

Whole-rock Composition

The major element composition of Lafayette is similar to Nakhla. Schmitt and Smith (1963) and Haskin *et al.* (1966) first reported REE analyses of Nakhla and Lafayette and recognized that they were generally similar in compositional patterns to terrestrial basalts (table III-1). However, already in the 1960s, they noted the difference in Sc contents between these meteorites and terrestrial basalts.

Boctor *et al.* (1976) reported the analysis of the fusion crust. Gibson *et al.* (1985), Dreibus *et al.* (1999, 2003), Sawyer *et al*. (2000) Middlefehldt 1997 and Wang *et al.* (1998) have determined trace elements.

Karlsson *et al.* (1992) reported a total of 0.387 wt. % H_2O in Lafayette. At least some of this is extra-terrestrial weathering, as evidenced by the isotopic ratios. Watson *et al.* (1994) also found high water content (0.38 wt. %) for Nakhla.

Lindstrom *et al.* (1996) and Treiman and Lindstrom (1997) have analyzed the "iddingsite" from Lafayette for trace elements (table III-2).

Radiogenic Isotopes

Using ^{4}He and ^{40}Ar, Ganapathy and Anders (1969) calculated "gas retention ages" of 0.83 Ga and 1.1 ± 0.3 Ga respectively for Lafayette. Podosek (1973) and Podosek and Huneke (1973) determined the age of Lafayette by the $^{39}Ar/^{40}Ar$ plateau technique (1.33 ±

Halogens *(in ppm)*	**F**	**Cl**	**Br**	**I**	**S**
Gibson *et al*. (1985)					420
					390
Sawyer *et al.* (2000)	57	147			477
	50	113			370
Dreibus *et al*. (1999)	74	100	0.59	.054	340
Dreibus *et al.* (2003)	74	101	0.59	.054	

0.03 Ga), but were hesitant to conclude that this was the crystallization age (figure III-7). Shih *et al.* (1998) determined a Rb-Sr age of 1.27 ± 0.07 Ga (I_{Sr} = 0.70260 ± 14) and a Sm-Nd age of 1.32 ± 0.05 Ga (figures III-8 and 9).

Swindle *et al.* (1997) have attempted to date the "iddingsite" and reported *"K-Ar ages of a few hundred million years"* (figure III-11). Swindle *et al.* (2000) reported K-Ar ages that ranged from zero to 670 Ma. Shih *et al.* (1998) determined a Rb-Sr age of about 700 Ma using carefully leached samples containing "iddingsite" (figure III-11). *Using U-Pb, Chen and Wasserburg (1986b) were the first to note something peculiar about the "brownies" in Nakhla.*

Cosmogenic Isotopes and Exposure Ages

Using ^{3}He, ^{21}Ne and ^{38}Ar, Ganapathy and Anders (1969) calculated an average cosmic-ray exposure age of 9.8 Ma for Lafayette. Podosek (1973) determined 6.5 Ma as the cosmic-ray exposure, but Bogard *et al.* (1984b) calculated ~11 Ma cosmic-ray exposure age of Lafayette. Using ^{14}C, Jull *et al.* (1993, 1997) originally determined a terrestrial age of ~8.9 ± 1.3 thousand years. Jull *et al*. (1999) revised the terrestrial age to 2,900 ± 1,000 years based on the ^{14}C/^{10}Be ratio and comparison with data from Nakhla *(with a known terrestrial age)*.

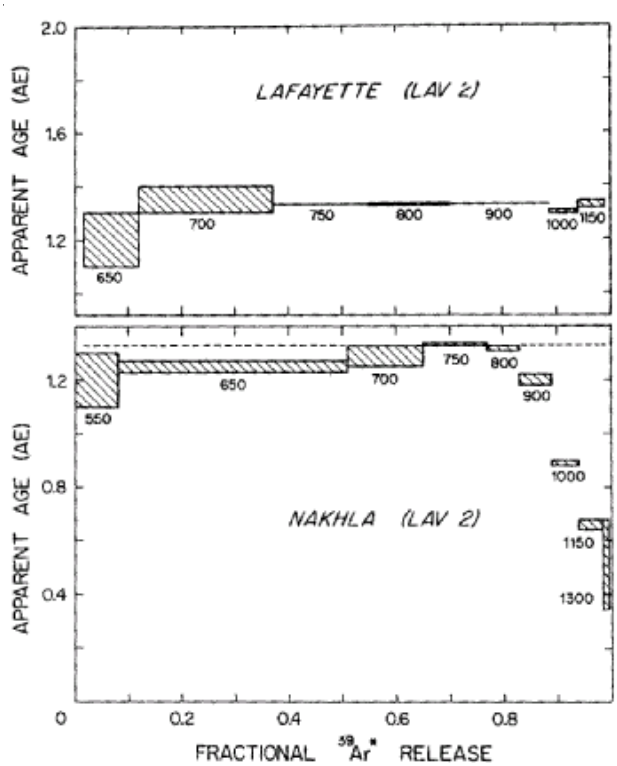

Figure III-7. *Argon plateau diagram for Lafayette and Nakhla meteorites from Podosek (1973). This is a copy of figure 3 in EPSL* ***19****, 142.*

On the basis of similar Xe isotopic compositions, Rowe *et al.* (1966) originally suggested that Lafayette and Nakhla are 'one and the same meteorite'. They noted that both Nakhla and Lafayette lacked detectable decay products of ^{244}Pu, but they observed excesses of ^{129}Xe which they inferred came from extinct ^{129}I (*see Hohenberg thesis, Podosek discussion*). *The excess* ^{129}Xe *is now generally interpreted as addition from Martian atmosphere*.

Other Isotopes

Taylor *et al.* (1965) originally reported the oxygen isotopic composition of pyroxenes from Lafayette and noted the difference from other achondrites. Clayton and Mayeda (1983, 1996) reported the oxygen isotopes for Lafayette and revised the data of Clayton *et al.* (1976). Karlsson *et al.* (1992) found that the oxygen isotopes in water released from Lafayette was enriched in ^{17}O, indicating that the past hydrosphere on Mars was from a different reservoir than the lithosphere. Clayton (1993a) reported the ^{18}O/^{16}O composition of olivine and pyroxene from Lafayette and calculated the equilibrium temperature. Romanek *et al*. (1996a, b, 1998) reported additional oxygen isotope data for various minerals, including "iddingsite". Farquhar and Thiemens (2000) found that the Δ^{17}O anomaly was in acid-soluble carbonate within the "iddingsite".

Kerridge (1988), Watson *et al.* (1994) and Leshin *et al*. (1996) found that deuterium was greatly enriched in Lafayette (figure III-10). Molini-Velsko *et al.* (1986) reported the isotopic composition of Si and found that

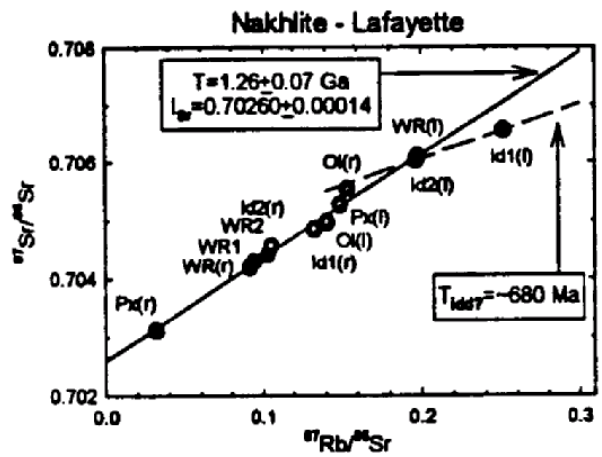

Figure III-8. *Rb-Sr internal mineral isochron for Lafayette Meteorite (from Shih et al. 1998).*

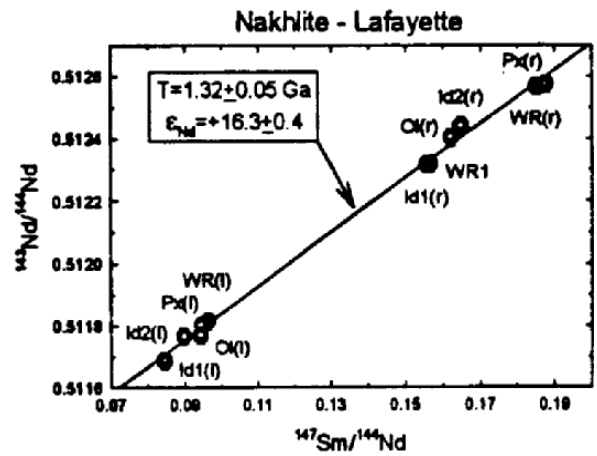

Figure III-9. *Sm-Nd internal mineral isochron for Lafayette meteorite (from Shih et al. 1998).*

it was normal. Farquhar *et al.* (2000) and Greenwood *et al*. (2000) have determined the isotopic composition of S. The carbon and nitrogen content and isotopic composition has been reported by Wright *et al.* (1992). Kerridge (1988) also determined the isotopic composition of carbon.

Lee and Halliday (1997) reported excess ^{182}W and Harper *et al.* (1995) reported excess ^{142}Nd.

Extra-terrestrial Weathering *(see section on "Iddingsite")*

Treiman *et al.* (1993) showed that the hydrous alteration in the cracks of Lafayette preceded the formation of the fusion crust, thus the alteration is pre-terrestrial *(see also the discussion in Nakhla).* Lindstrom *et al.* (1996) and Treiman and Lindstrom (1997) found that the weathering products in Lafayette were enriched in Hg, Br and alkali elements, however, the sample used in this study may have been contaminated while it was in the chemistry laboratory at Purdue. Vicenzi and co-authors have also been carefully studying the alteration products in Lafayette. Greenwood *et al.* (1998) have studied the isotopic composition of sulfides in Lafayette and speculate that they may have been modified by alteration on Mars. Ar age-dating and Xe, Kr isotopic analysis of carefully hand-picked iddingsite separates are consistent with formation on Mars (Swindle *et al.* 2000). Bridges and Grady (2000) conclude that the "salts" located in the Lafayette alteration (iddingsite) formed by fractional evaporation of an acid brine on Mars *(although it is perhaps surprising, that they were not leached-out or modified during the ~3000 years on the ground in Illinois!).*

Processing

The very fresh appearance of the fusion crust of caused Nininger (1935) to observe that Lafayette *"... had not lain on the Earth for very long time before it was picked up and protected against abuses of a mechanical*

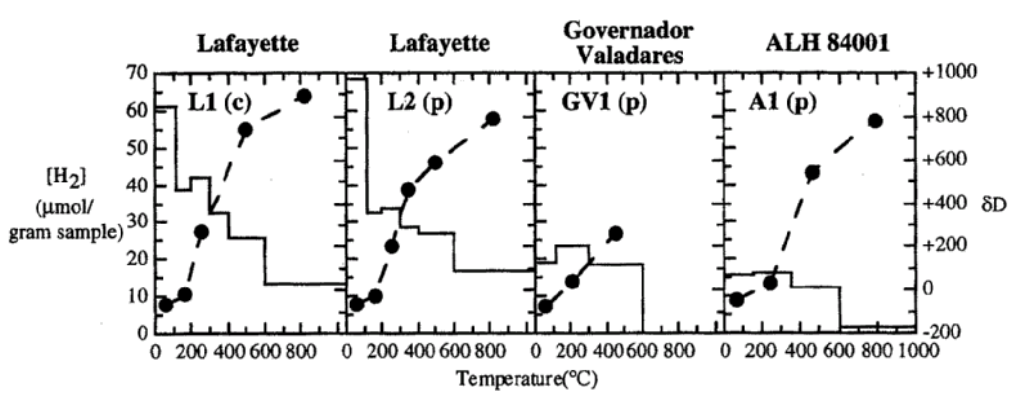

Figure III-10. *Isotopic composition of hydrogen in Lafayette meteorite from Leshin et al. (1996). This is a copy of figure 2 in GCA* ***60****, 2640. Note that the water is still coming off at the high temperature steps (>800C).*

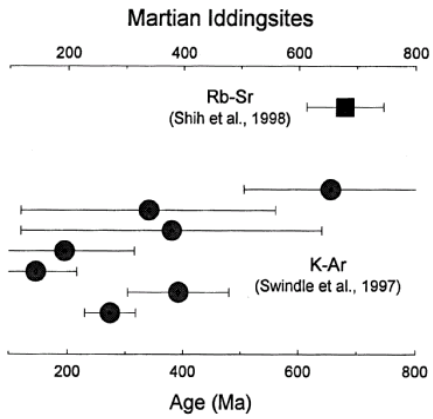

Figure III-11. *"Ages" reported for "iddingsite" from Lafayette. This figure was kindly provided by C.-Y. Shih.*

nature". However, the terrestrial exposure age obtained by Jull *et al*. is on the order of ~3,000 years. Originally the whole specimen was curated at Purdue University. The main mass of Lafayette is now curated at the Smithsonian Institution in Washington, after the Field Museum (Chicago) obtained excellent photos of the fine ablation features on the conical surface (figures III-1-3). The Field Museum retained a large piece.