Reference List

NWA 998 – 456 grams

Nakhlite

Figure 1: *Photos of NWA 998 (from Jim Strope's web site).*

Introduction

Irving *et al.* (2002) reported that a piece of a nakhlite was acquired in Morocco in September 2001 (figure 1). Figure 2 shows what appears to be a broken "slab", with a fusion crust around the outside.

It is 1.3 b.y. old, with an exposure to cosmic rays of ~ 11 m.y. It is the most crystalline of the Nakhlites, which are all somehow related.

Petrography

The texture of NWA 998 is that of a hypabyssal, adcumulate igneous rock. According to Irving *et al.* (2002), the crystallization sequence was olivine, orthopyroxene, titanomagnetite, augite, apatite and plagioclase (figures 3 and 4). Treiman (2005) compares NWA998 with the other nakhlites. Treiman finds that the mesostasis has completely crystallized. But the definitive paper on the petrology of NWA998 will be the one by Treiman and Irving (2008), where they explain in great detail, everything that can be read from this pretty rock.

As in other nakhlites, shock appears minimal, because the plagioclase remains birefringent. There is some twining in the augite, which may be due to shock.

Preterrestrial alteration also appears minimal.

Mineral Chemistry

Olivine: Irving et al. (2002) reported olivine is Fo_{36}. Mikouchi et al. (2006) report Fo_{40}.

Pyroxenes: Irving et al. and Treiman (2006) found the dominant mineral is clinopyroxene $Wo_{39}En_{78}$, with minor the nakhlites (figure 5) (slowest cooling?). Pyroxene

Mineralogical Mode for NWA998

	Treiman 05	Treiman + Irving 2008
Olivine	10 vol. %	9
Augite	68	75
Orthopyroxene	2	3.5
Plagioclase		7
Magnetite		1
Other	19	5

Figure 2*: Photograph of 165 g end piece of NWA 998 by Adam and Greg Hupé (with permission)*

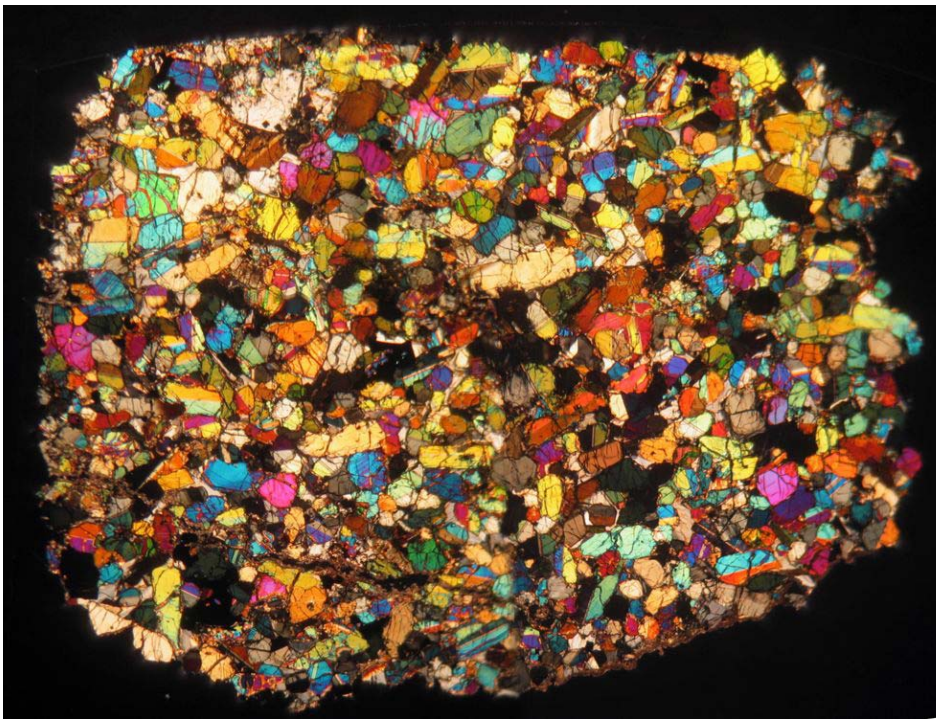

Figure 3: *Photomicrograph of thin section of NWA998 (by John Kashuba). This is photo is with crossed polarizers.*

contains tiny melt inclusions. Wadhwa et al. (2004) have reported the REE contents of augite cores and melt inclusions.

Plagioclase: Interstitial plagioclase exhibits normal birefringence and is An_{39}. Mikouchi et al. (2006) report that some grains are up to 500 microns.

Opaques: Intergrowths of titanomagnetite and lo-Ca pyroxene are present at grain boundaries between large, discrete olivine and titanomagnetite grains. Cr-titanomagnetite inclusions occur within olivine.

Secondary minerals: Ankeritic carbonate, K-feldspar, (?) serpentine, calcite and a Ca-sulfate are present on

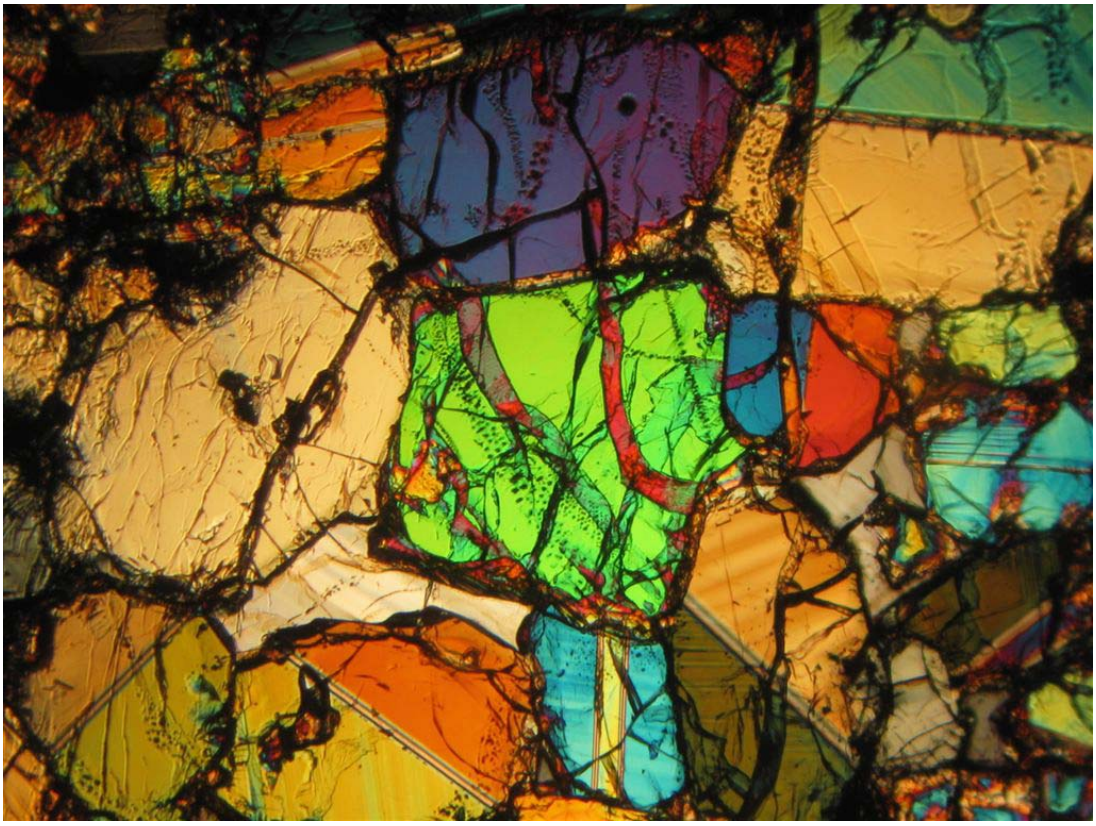

Figure 4: *Thin section photomicrograph of NWA 998, field of view 1.54 mm wide. Crossed polarizers. Photo taken by John Kashuba (reprinted with permission).*

grain boundaries. Irving *et al.* (2002) suggested that some of these *secondary minerals* may have a pre-terrestrial origin! But Treiman and Irving (2008) find that only the "iddingsite" is of martian orgin.

Phosphate: The phosphate in NWA998 is apatite, which is concentrated in zones. Wadhwa et al. (2004) have reported the REE abundance of apatite in NWA998. Treiman and Irving (2008) determined the composition of apatite as $Ca_5(PO_4)_3(Cl_{0.5}F_{0.3}OH_{0.2})$. Channon et al. (2011) determined F, Cl, H and S in the apatite.

Whole-rock Composition

Treiman and Irving (2008) determined the composition of NWA998 two ways; 1) by measuring the composition of the fusion crust and 2) by carefully measuring the mineralogic mode and factoring the mineral compositions. A calculated REE pattern shows NWA998 has similar composition to the other nakhlites (figure 6). Dreibus et al. (2006) report 88 ppm F, 127 ppm Cl, 0.18 ppm Br, 0.281 ppm I, 280 ppm S and 1324 ppm carbon.

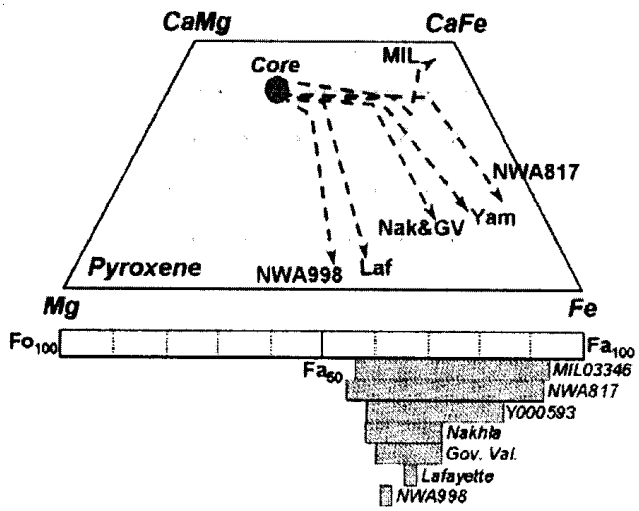

Figure 5: *Composition of pyroxene and olivine in NWA998 compared with other nakhlites (Mikouchi et al. 2006).*

Radiogenic Isotopes

A Sm-Nd isochron has been determined by Carlson and Irving (2004), yielding a crystallization age of 1.29 ± 0.05 b.y. (figure 7). U-Pb, Rb-Sr and Lu-Hf isotope systems were disturbed or contaminated. Garrison and Bogard (2005) reported the crystallization age as 1.332 ± 0.008 b.y. (figure 8).

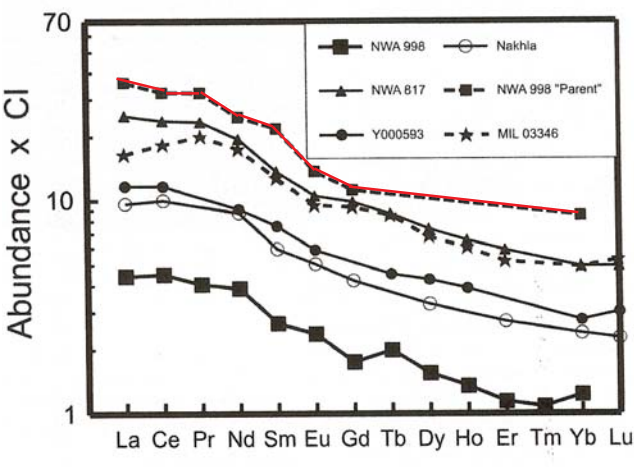

Figure 6: *Calculated composition for REE in bulk NWA998, compared with measured compositions of other Nakhlites (from Treiman and Irving 2008).*

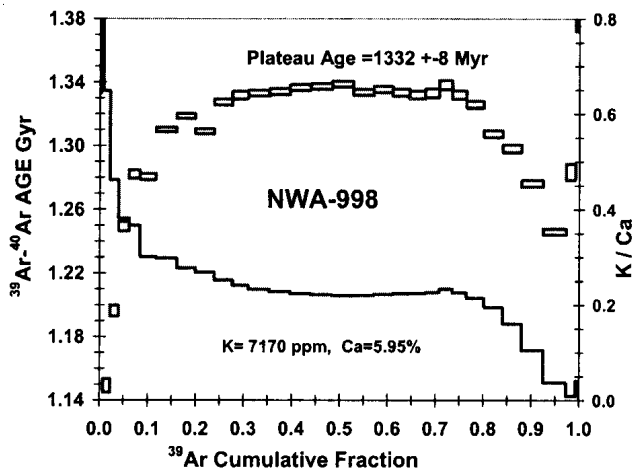

Figure 8: *Garrison and Bogard (2005) reported the Argon release pattern.*

Cosmogenic Isotopes

The ^{38}Ar cosmic ray exposure age of NWA998 (9.3 m.y.) was determined by Garrison and Bogard (2005). The ^{14}C terrestrial age of NWA998 is 6 ± 1 k.y. (Nishiizumi et al. 2004). Nishiizumi et al. also report ^{10}Be and ^{41}Ca.

Other Isotopes

Oxygen isotopes of acid-washed augite as determined by D. Rumble (reported by Irving), were ä^{18}O = +3.9 ± 0.2, ä^{17}O = +2.2 ± 0.01 and Ä^{17}O = + 0.24 ± 0.01 ‰.

Boctor et al. (2005) used secondary ion mass spectroscopy to determine the volatile (H_2O, CO_2, F, S and Cl) content of minerals in NWA998 and the isotopic ratio of hydrogen/deuterium.

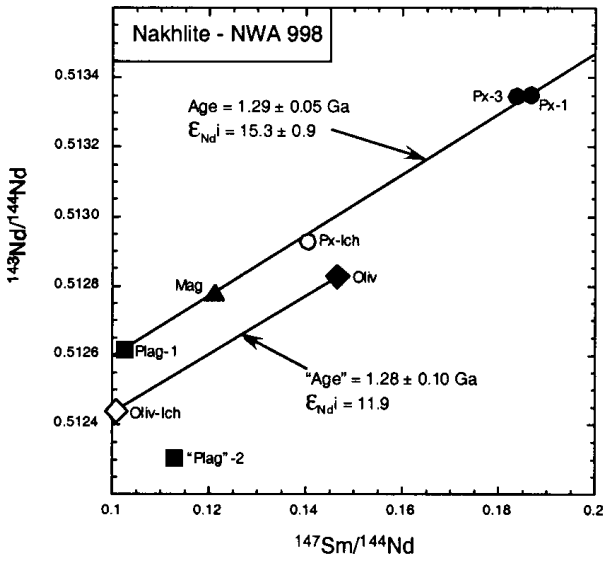

Figure 7: *Sm-Nd isochron for NWA998 by Carlson and Irving (2004).*

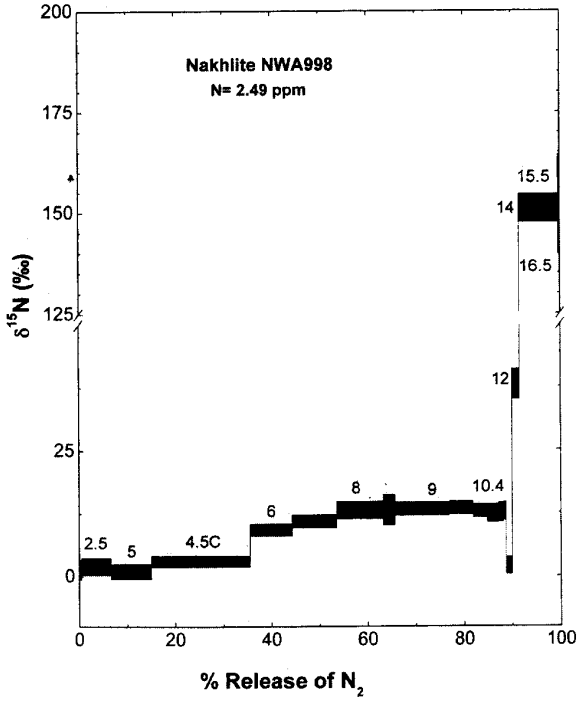

Figure 9: *Nitrogen isotopes as function of release temperature showing that NWA998 has a high temperature component of strange gas (from Mathew and Marti 2005).*

Mathew and Marti (2005) reported isotopic data for gas (N_2, Ar and Xe) released during heating experiments (figure 9). It is consistent with gas released in similar experiments on Chassigny and the other nakhlites. The He and Ne isotopic data by Garrison and Bogard (2005) need to be considered in this light (*there appears to be a mystery component*).

Table 1. Chemical composition of NWA 998.

reference	Treiman08			
weight				
SiO2 %	47.4	(a)	49.1	(b)
TiO2	0.5	(a)	0.5	(b)
Al2O3	2	(a)	2.8	(b)
FeO	18.4	(a)	17.6	(b)
MnO	0.5	(a)	0.5	(b)
MgO	11.7	(a)	11.7	(b)
CaO	13.8	(a)	14	(b)
Na2O	0.6	(a)	0.8	(b)
K2O	0.15	(a)	0.3	(b)
P2O5			0.1	(b)
S %				
sum				
Sc ppm				
V				
Cr				
Co				
Ni				
Cu				
Zn				
Ga				
Ge ppb				
As				
Se				
Rb				
Sr				
Y				
Zr				
Nb				
Mo				
Ru				
Rh				
Pd ppb				
Ag ppb				
Cd ppb				
In ppb				
Sn ppb				
Sb ppb				
Te ppb				
Cs ppm				
Ba				
La			1	(c)
Ce			2.8	(c)
Pr			0.37	(c)
Nd			1.7	(c)
Sm			0.38	(c)
Eu			0.13	(c)
Gd			0.35	(c)
Tb			0.07	(c)
Dy			0.38	(c)
Ho			0.07	(c)
Er			0.18	(c)
Tm			0.024	(c)
Yb			0.2	(c)
Lu				
Hf				
Ta				
W ppb				
Re ppb				
Os ppb				
Ir ppb				
Pt ppb				
Au ppb				
Th ppm				
U ppm				

technique: (a) emp, fusion crust, (b) calculated from mode, (c) calculated from Wadhwa + mode

References for NWA998