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 twinning in the augite, which may be due to shock.

Preterrestrial alteration also appears minimal.

Mineral Chemistry

Pyroxenes: Irving et al. and Treiman (2006) found the dominant mineral is clinopyroxene Wo39En61, with minor the nakhlites (figure 5) (slowest cooling?). Pyroxene

<table>
<thead>
<tr>
<th>Mineralogical Mode for NWA998</th>
<th>Treiman 05</th>
<th>Treiman + Irving 2008</th>
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</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>10 vol.%</td>
<td>9</td>
</tr>
<tr>
<td>Augite</td>
<td>68</td>
<td>75</td>
</tr>
<tr>
<td>Orthopyroxene</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>19</td>
<td>5</td>
</tr>
</tbody>
</table>
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 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.
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).

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

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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 origin.

**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 $\text{Ca}_5(\text{PO}_4)\left(\text{Cl}_{0.5}\text{F}_{0.3}\text{OH}_{0.2}\right)$. 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.

**Radiogenic Isotopes**
A Sm-Nd isochron has been determined by Carlson and Irving (2004), yielding a crystallization age of $1.29 \pm 0.05$ 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 $1.332 \pm 0.008$ b.y. (figure 8).
**Cosmogenic Isotopes**

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

**Other Isotopes**

Oxygen isotopes of acid-washed augite as determined by D. Rumble (reported by Irving), were $\delta^{18}\text{O} = +3.9 \pm 0.2$, $\delta^{17}\text{O} = +2.2 \pm 0.01$ and $\Delta^{17}\text{O} = +0.24 \pm 0.01$‰.

Boctor et al. (2005) used secondary ion mass spectroscopy to determine the volatile (H$_2$O, CO$_2$, F, S and Cl) content of minerals in NWA998 and the isotopic ratio of hydrogen/deuterium.

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.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Treiman08</th>
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<tbody>
<tr>
<td>weight</td>
<td></td>
</tr>
<tr>
<td>SiO2 %</td>
<td>47.4 (a) 49.1 (b)</td>
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<tr>
<td>TiO2</td>
<td>0.5 (a) 0.5 (b)</td>
</tr>
<tr>
<td>Al2O3</td>
<td>2 (a) 2.8 (b)</td>
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<tr>
<td>FeO</td>
<td>18.4 (a) 17.6 (b)</td>
</tr>
<tr>
<td>MnO</td>
<td>0.5 (a) 0.5 (b)</td>
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<tr>
<td>MgO</td>
<td>11.7 (a) 11.7 (b)</td>
</tr>
<tr>
<td>CaO</td>
<td>13.8 (a) 14 (b)</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.6 (a) 0.8 (b)</td>
</tr>
<tr>
<td>K2O</td>
<td>0.15 (a) 0.3 (b)</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.1 (b)</td>
</tr>
</tbody>
</table>

S %

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

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