Northwest Africa 032, 479

Unbrecciated basalt

~300, 156 g

Figure 1: Cut face of a piece of NWA 479 ((photo courtesy of B. Fectay and C. Bidaut).

Introduction

Northwest Africa (NWA) 032 was found in the Saharan desert in October 1999, and weighs approximately 300 g. The stone is covered with fusion crust, but the exterior also has patches of white calcite and also red to orange ferric oxide or oxyhydroxide (Fagan et al., 2002; Korotev et al., 2001). The interior is an unaltered unbrecciated crystalline basalt with phenocrysts of olivine, pyroxene and chromite (Figs 2 and 3). A paired stone, NWA 479 (Fig. 1) weighing 156 g (Barrat et al., 2001, 2005), is the exact missing half as matched by the respective owners (B. Fectay, personal communication, 2007).

Petrography and Mineralogy

Olivine (11.3%), Pyroxene (4.8%), and chromite (0.3%) phenocrysts are in a groundmass (80.4%) of feldspar, pyroxene, ilmenite, troilite and metal. There are ubiquitous shock melt veins (3.2%). Olivine phenocrysts are zoned from Fo_{66} cores to Fo_{50} rims. Pyroxenes exhibit a large compositional range from low Ca bronzites to close to pyroxferrite at the FeO-rich end (Fig. 4). Pyroxenes from NWA 479 completely overlap

Figure 2: close up of cut slab of NWA 032 illustrating the olivine phenocrysts in a dark grey groundmass.

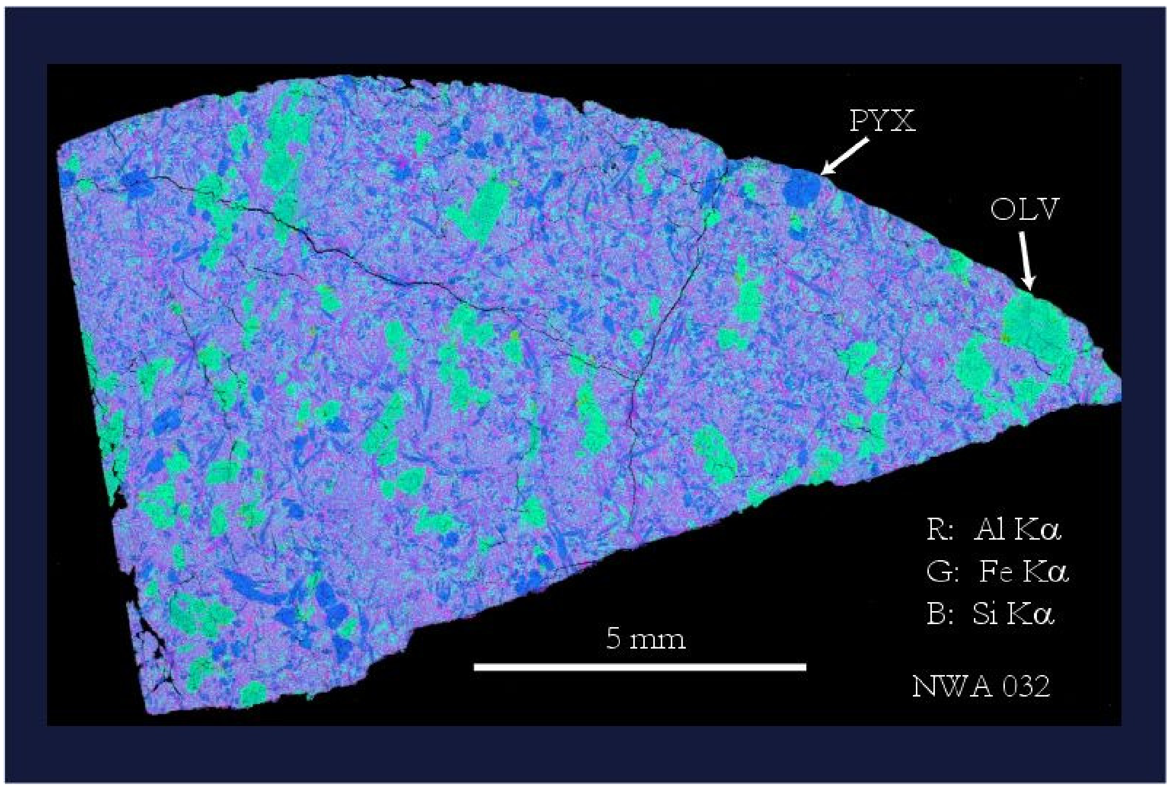


Figure 3: X-ray map of a thin section of NWA 032 showing green olivine phenocrysts, blue pyroxenes, and a purplish groundmass (from Fagan et al., 2003).

those found in NWA 032 (Fig. 5). Chromites are zoned from Cr-rich cores to ulvospinel rims (Fig. 6). Undulatory/mosaic extinction in the olivine and pyroxene, along with the presence of ringwoodite and wadsleyite in shock melt veins from NWA 479, attest to the high shock state of these meteorites.

Textures similar to that of NWA 032 have been experimentally reproduced by initial slow cooling to form olivine phenocrysts followed by more rapid cooling (5 °C/hr) to form the pyroxene-rich mesostasis (Koizumi et al., 2006). Such a sample could have formed near the top (close to the chilled margin) of a large basaltic magma body represented by the NWA and LAP lunar meteoritic basalts (Day and Taylor, 2007).

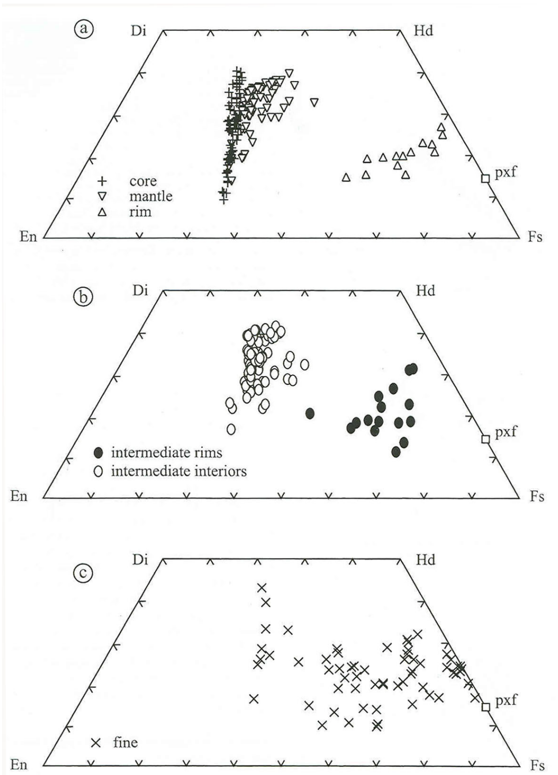
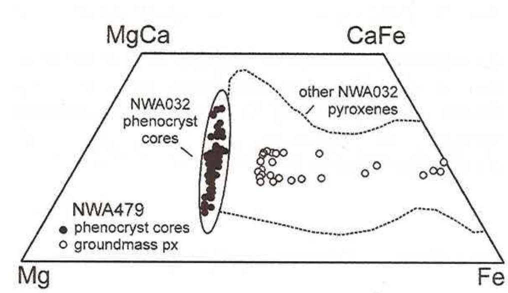


Figure 4: Pyroxene compositions from NWA 032 including phenocrysts (top), intermediate (middle) and fine grained (bottom) (from Fagan et al., 2002).

Figure 5: compositions from NWA 479 showing overlap with NWA 032 pyroxenes (from Barrat et al., 2005).



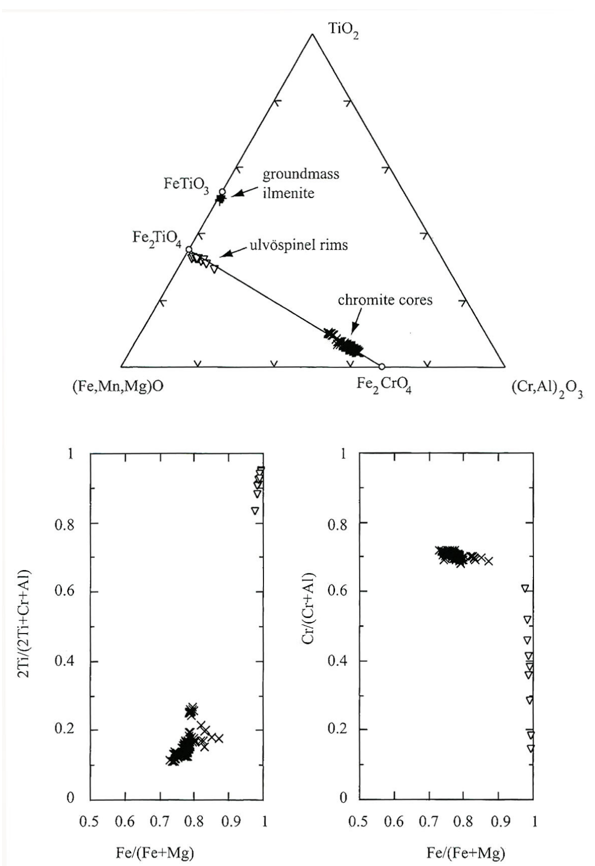


Figure 6: Spinel cores and rims from NWA 032 (Fagan et al., 2002).

Chemistry

NWA 032 has a composition very similar to low Ti basalt such as those found in the Apollo 12 and 15 collection (Fig. 7 and 8; Table 1). It represents a liquid composition because the olivine phenocryst cores are identical in composition to those expected from the bulk composition and Mg-Fe Kd (Fagan et al., 2002). Both NWA 032 and NWA 479 exhibit LREE enrichment (Fig. 9 and 10), have high Th/Sm. The latter cannot be due to magmatic fractionation from a more familiar parental liquid, since there is no known major phase that will fractionate these two elements. Instead it may be from a region of the Moon unsampled by Apollo or Luna collections. This has also been suggested based on the depleted Nd isotopic values, coupled with LREE/HREE and Th/HREE (Borg et al., 2007). Additionally, olivine phenocrysts record variable and heavy Li isotopic composition, having δ^7Li as high as +15, compared to much lower (0 to +4) for terrestrial mantle (Barrat et al., 2005). The variation has been ascribed to diffusivity control, but the heavy character of the values has been attributed to the giant impact that formed the Moon.

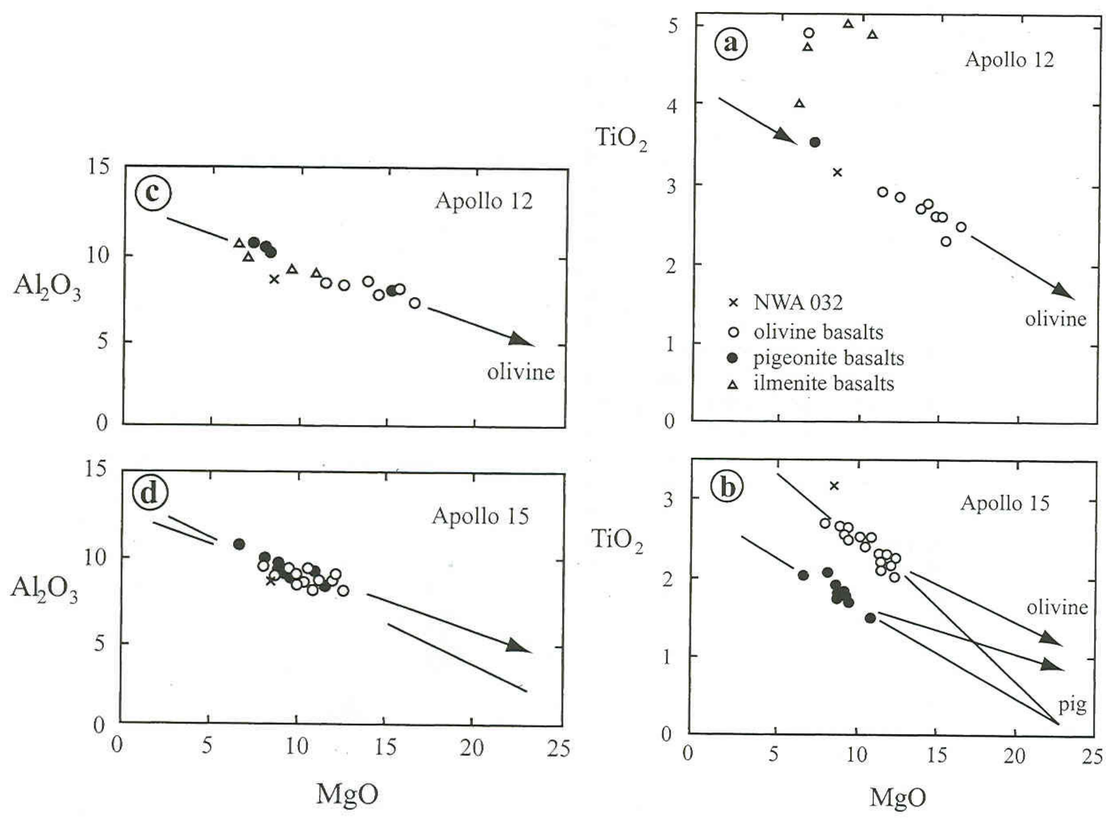


Figure 7: Al_2O_3 vs. MgO for NWA 032 (x) compared to Apollo 12 and 15 basalts.
Figure 8: TiO_2 vs. MgO for NWA 032 (x) compared to Apollo 12 and 15 basalts, showing fractionation vector for olivine and pigeonite (from Fagan et al., 2002).

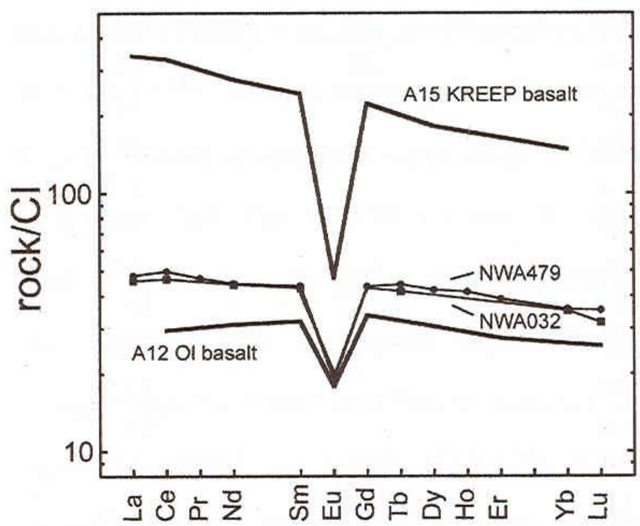


Figure 9: Rare earth element patterns for NWA 032 and 479, compared to Apollo 12 olivine basalt and KREEP illustrating their LREE nature (from Barrat et al., 2005).

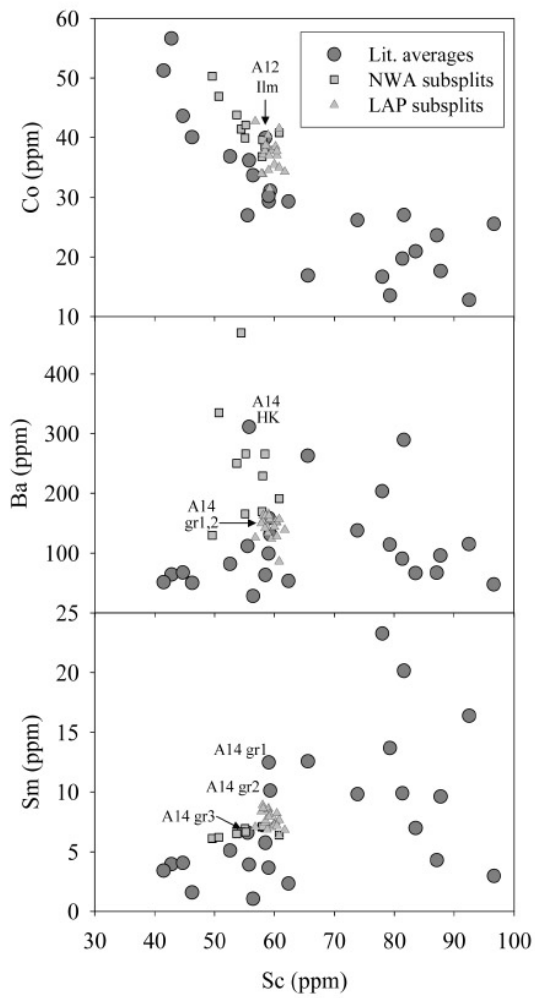


Figure 10: Co, Ba and Sm vs. Sc (all in ppm) for the NWA 032 subsamples analyzed by Zeigler et al. (2005), compared to average mare basalt compositions from the Apollo and Luna missions (dark grey circles).

Radiogenic age dating

^{39}Ar-^{40}Ar plateau ages for splits of NWA 032 and NWA 479 yield similar ages of 2775 and 2734 Ma, respectively (Fig. 11; Fernandes and Burgess, 2006b; Fagan et al., 2002; Fernandes et al., 2003; Fernandes et al., 2009). Also, Rb-Sr and Sm-Nd ages of 2852 (±65) and 2692 (±160) Ma have been measured in NWA 032, within error of the Ar-Ar ages (Borg et al., 2007). More recent ages reported by Borg et al. (2009) for NWA 032 are slightly higher, but nonetheless consistent with a young overall age for NWA 032 and 479 (Fig. 12 and 13).

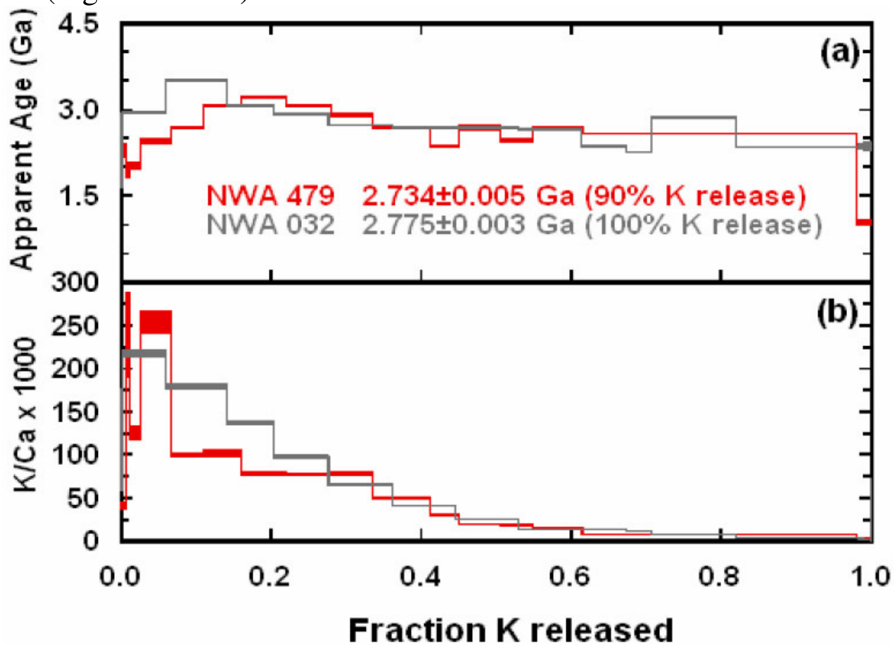


Figure 11: Comparison of apparent age and Ca/K for NWA 032 and NWA 479 (from Fernandes and Burgess, 2006b, Fernandes et al. 2009).

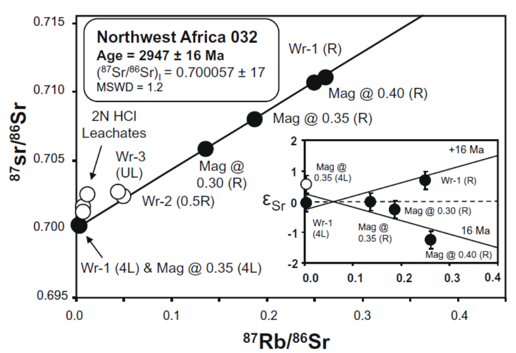


Figure 12: Rb-Sr isochron and age of 2947 ± 16 Ma determined by Borg et al. (2009) for NWA 032.

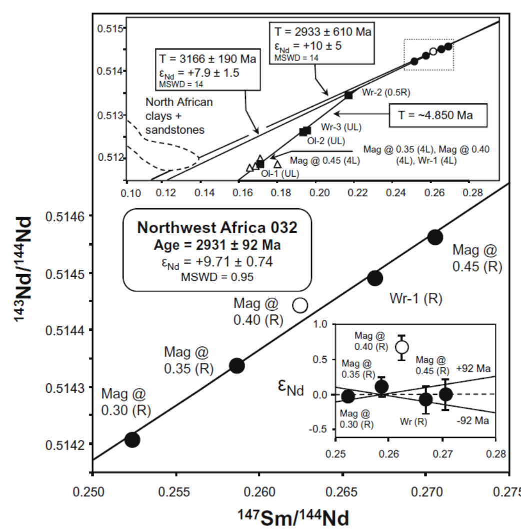


Figure 13: Sm-Nd isochron and age of 2931 ± 92 Ma determined by Borg et al. (2009) for NWA 032.

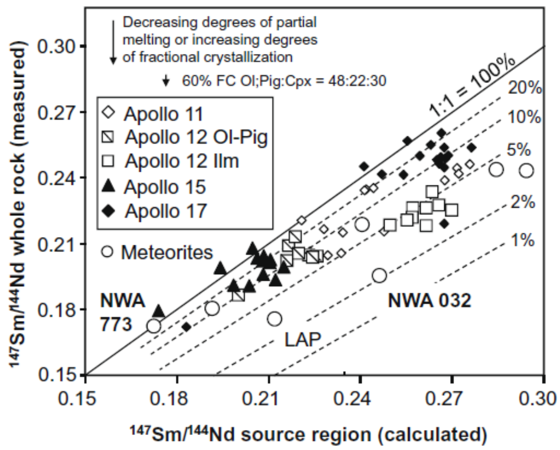


Figure 14: Sm-Nd systematics of basaltic meteorites and Apollo basalts showing that the low Sm/Nd whole rock and source region for NWA 032 can be explained by small degrees of partial melting of a KREEP-free source (from Borg et al., 2009).

Consideration of Sm-Nd systematics for NWA 032, NWA 773, LAP basaltic meteorites, and a wide range of Apollo basaltic rocks indicates that NWA 032 can be explained by variable degrees of melting of source that does not involve KREEP (Figure 14).

Cosmogenic isotopes and exposure ages

Residence time in the lunar regolith has been measured by Fernandes et al. (2003) and Lorenzetti et al. (2005) at 212 Ma and 207 Ma, respectively. The large fluence of 2.58 x 10^{16} n cm^{-2} is also consistent with the large CRE (Hidaka and Yoneda, 2006). However, Lorenzetti et al. (2005) argue that NWA 032 experienced a multi-stage exposure at different shielding depths. The transit time from Moon to Earth was 0.042 Ma, terrestrial residence time < 0.01 Ma, and a therefore a time of ejection of 0.05 Ma (Lorenzetti et al., 2005).

Table 1a. Chemical composition of NWA 032/479

reference	1	2	3	4	5
weight				25.69	124
technique	a,b,d	d	b	b	d
SiO_2 %	44.7				44.7
TiO_2	3.08		3.15	3.19	3
Al_2O_3	8.74		9.48		9.32
FeO	23	22.1	20.94		22.2
MnO	0.33		0.29		0.28
MgO	8.45		7.21		7.97
CaO	10.9		10.99		10.6
Na_2O	0.37	0.347	0.34		0.35
K_2O	0.11		<0.1		0.09

P_2O_5				0.09
S %				
sum				99
Sc ppm	56	61		55.2
V		132		
Cr	2744	2614		2760
Co	42	40.6		42.1
Ni	50	49.2		
Cu		34.2		
Zn		30.5		
Ga		4.31		
Ge				
As				
Se				
Rb		1.78		
Sr	142	132		149
Y		65.71	52.8	
Zr	175	206		170
Nb		15.26		
Mo				
Ru				
Rh				
Pd ppb				
Ag ppb				
Cd ppb				
In ppb				
Sn ppb				
Sb ppb				
Te ppb				
Cs ppm		0.051		
Ba	242	371		266
La	11.2	11.75	11.29	11.3
Ce	29.7	31.77	30.58	29.9
Pr		4.52	4.22	
Nd	21	21.21	20.68	20
Sm	6.61	6.73	6.68	6.63
Eu	1.1	1.13	1.14	1.1
Gd		8.9	8.55	
Tb	1.56	1.66	1.62	1.57
Dy		10.73	10.56	
Ho		2.35	2.26	
Er		6.46	6.58	
Tm			0.9	
Yb	5.79	5.86	5.81	5.8
Lu	0.802	0.893	0.93	0.8
Hf	5	5.05		5.02
Ta	0.62	0.8		0.63
W ppb		310		

Re ppb				
Os ppb				
Ir ppb				
Pt ppb				
Au ppb	4			
Th ppm	1.9	2.01	2.13	1.89
U ppm	0.45	0.46	0.4	0.46

technique (a) FB-EMPA, (b) ICP-MS, (c) IDMS, (d) INAA

Table 1b. Light and/or volatile elements for NWA 032

Li ppm		12.69		
Be		1.22		
C				
S				
F ppm				
Cl				
Br				
I				
Pb ppm		1.02		
Hg ppb				
Tl				
Bi				

1) Fagan et al. (2002); 2) Korotev et al. (2001); 3) Barrat et al. (2002); 4) Borg et al. (2009); 5) Ziegler et al. (2005)