NORTHWEST AFRICA 176 A UNIQUE IRON METEORITE WITH SILICATE INCLUSIONS RELATED TO BOCAIUVA. Menghua Liu[1], E. R. D. Scott[1], K. Keil[1], J. T. Wasson[2], R. N. Clayton[3], T. Mayeda[3], O. Eugster[4], G. Crozaz [5], and C. Floss[5], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA, [2]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA, [3]Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637 USA, [4]Universitat Bern, Physikalisches Institut, Sidlerstrasse 5, CH-3012, Bern, Switzerland, [5]Washington University, Box1169, St Louis, Missouri 63130 USA.

Introduction: The Northwest Africa 176 iron meteorite with silicate inclusions was found at the border of Morocco and Algeria in 1999. We have studied a 68 g slice from the 2 kg mass. The meteorite contains greenish-yellow numerous polymineralic silicate inclusions embedded in a metallic matrix. Large inclusions up to 1 cm across tend to be round or equant, small ones are more irregular in shape. Our data indicate that the meteorite is related to Bocaiuva.

Petrography: The modal proportion of minerals in the meteorite (Table 1) were estimated using a method based on element x-ray intensity maps for 10 elements collected with the electron microprobe.

Table 1. Mineral modal composition (vol.%)

olivine	opx	cpx	plag	merrillite	chromite
20.9	17.5	1.3	3.9	0.2	0.1
kama	taen	schr	troi	total	silicates
49.2	4.7	1.6	0.6	100.0	43.7

Comparison of the abundance of silicate inclusions in NWA 176 and the Guarena H6 chondrite (Table 2) suggests that those in NWA 176 are approximately chondritic in composition. REE analysis will test this.

Table 2. Silicate mineral modal composition (vol.%)

	olivine	opx	cpx	plag
NWA 176	47.9	40.1	3.0	9.0
Guarena H6	39.2	40.8	8.6	11.4
H chond.*	44.9	34.0	5.4	15.7

*Calculated mineral modal composition from bulk composition of meteorite [1].

None of the silicate inclusions show relict chondrules but some have radially zoned mineralogy. A few consist of a large olivine crystal (0.5-1.5 mm) surrounded by smaller opx grains (0.1-0.3 mm) and rare olivine (Fig. 1). In contrast, the large silicate inclusions at the left edge of Fig. 1 appears to be derived from an object with a core of large opx crystals (0.5-0.8 mm) surrounded by a rim of small mafic minerals (0.1-0.3 mm), mainly olivine. Plagioclase grains throughout the section are commonly 0.1-0.2 mm in size. In some regions, the smallest silicate grains are not randomly distributed and appear to be aligned.

Silicates have equigranular, recrystallized textures with 120^o triple-junctions. Some olivines contain kink bands implying that the olivine experienced deformation while hot and plastic. The recrystallized metal-silicate borders show that the silicates were metamorphosed in situ.

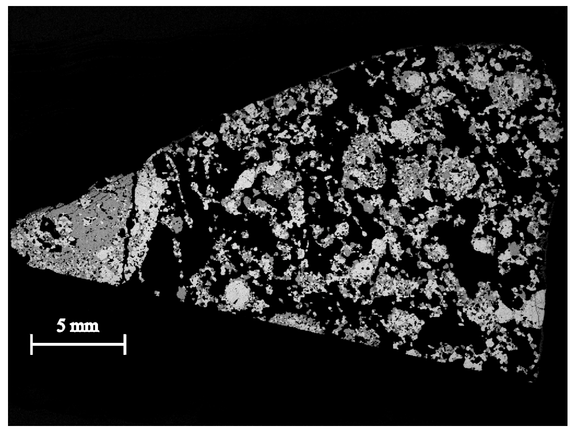

Figure 1. X-ray map for Mg Kα. 1024 $\times$ 768 pixels. Dark gray – opx; light gray – olivine; black – very largely metal.

Etching revealed oriented kamacite lamellae with widths of 0.15-0.35 mm in the largest silicate-free area of the metal.

Mineral chemistry and geochemistry: Analyses of 250 silicate grains show that the minerals are homogeneous. Olivine has an average composition of Fa 11.4 $\pm$ 0.3 ($\pm$ 1σ) and 0.03 wt% CaO. Opx is enstatite with the composition of $Fs_{11.4\pm0.6}Wo_{2.7\pm0.4}En_{85.9\pm0.8}$. Cpx is augite or diopside with an average composition of $Fs_{5.9\pm0.7}Wo_{42.2\pm2.4}En_{51.8\pm1.9}$. Plagioclase is very rich in CaO. The average composition is $An_{49.9\pm2.7}Ab_{46.5\pm2.2}Or_{3.6\pm0.7}$.

Taenite grains are zoned with M shaped distribution of Ni concentrations up to 36 wt%. Troilites in silicate inclusions and in metal are identical in composition.

INAA of a silicate-poor metal sample shows that NWA 176, although close in composition to group IIE and IIIAB, is an ungrouped iron resembling Bocaiuva (Table 3). Like the silicate-bearing Bocaiuva iron, NWA 176 has low Co, high Cu and a high Ge/Ga ratio: The two irons have almost identical compositions, suggesting they are closely related.

Table 3. INAA Analysis of Siderophile Elements

	Cr	Co	Ni	Cu	Ga	Ge
	μg/g	mg/g	mg/g	μg/g	μg/g	μg/g
NWA 176	523	4.13	86.6	318	17.7	~160
Bocaiuva	154	4.17	83.7	305	19.8	178
	As	W	Re	Ir	Pt	Au
	μg/g	mg/g	ng/g	μg/g	μg/g	μg/g
NWA 176	9.12	1.02	363	3.56	7.7	0.853
Bocaiuva	9.90	1.28	310	2.86		0.917

Oxygen isotopic composition: The oxygen isotopic compositions of silicate inclusions in NWA 176 are $\delta^{18}O$ = -2.5‰, $\delta^{17}O$ = -6.5‰. The only differentiated meteorites that are as ^{16}O-rich as NWA 176 are the Eagle Station-type pallasites and the ungrouped iron with silicate inclusions, Bocaiuva [2,3], again suggesting that NWA 176 is related to Bocaiuva.

Metamorphic temperature and cooling rate: Two-pyroxene equilibration temperatures were calculated from the compositions of coexisting opx and cpx using the Kretz method [4]. Calculated temperatures range from 970-1280°C with an average of 1100 ± 60°C (41 measurements in total). These temperatures are comparable to the highest temperatures estimated for acapulcoites [5] and winonaites [6].

Using the Wood [7] method and the Willis and Goldstein revised cooling rate curves [8], we estimated the cooling rate of the meteorite from the relationship between the Ni content at the center of taenite grains and their radius. Because of the limited availability of taenite in silicate inclusions, we used some elongated taenites in the iron matrix. Both types cooled at ~1000°C/Myr.

Discussion: Most iron meteorites with chondritic silicate inclusions are members of groups IAB, IIICD and IIE, but the mineralogy, metal and O isotopic compositions show that NWA 176 is not a member of these groups. Unlike IAB and IICD irons, NWA 176 also lacks graphite and appears to be FeS-poor.

We conclude that NWA 176 is closely related to the ungrouped iron meteorite with silicate inclusions, Bocaiuva. The silicate inclusions in Bocaiuva are generally chondritic and consist of major olivine (Fa7.7) and opx (Fs7.6) and minor plagioclase (Ab49, An49) and clinopyroxene (Fs7.6) [3]. These compositions are close to those in NWA 176. Both meteorites have abundant mm-to-cm sized silicate inclusions, some of which are rounded and aligned. Oxygen isotope compositions and siderophile element abundances of these two meteorites are almost identical.

Textures and mineral compositions show that NWA 176 was strongly metamorphosed. Relict chondrules are absent and Ca concentrations in olivine and low-Ca pyroxene are comparable to those in well metamorphosed chondrites. The two-pyroxene temperature of 1100°C is much higher than the Fe-Ni-S cotectic temperature, so S-rich melts may have been redistributed. The silicate fraction should also have experienced partial melting but such melts do not appear to have been lost. (REE analyses will help to clarify this.)

Three possible origins can be considered to account for the high metal/silicate ratio in NWA 176 and Bocaiuva. They may have formed from a partially melted asteroid that experienced some partial melting and breakup and reaccretion, as proposed for the parent body of IAB irons [9]. This model is less attractive for NWA and Bocaiuva as their silicate inclusions are more uniformly distributed and tend to be rounded not angular. However, this might reflect differences in thermal history.

Another possible origin is that NWA 176 and Bocaiuva are strongly metamorphosed, metal-rich chondrites. CB chondrites, which have higher metal abundances than NWA 176, are also depleted in Na and S and other volatiles [10]. Even though CB chondrites are all unmetamorphosed, it is likely that some metal-rich chondrites were strongly metamor-phosed as we have numerous irons that are depleted in Ga, Ge and other volatiles that may have formed from melted metal-rich chondritic asteroids. The radially zoned mineralogy of some NWA silicate inclusions, their sizes, and rather uniform distribution might have been inherited from metal-rich chondritic precursor material.

A third possibile origin for NWA and Bocaiuva is that both may have formed from a clast-free chondritic impact melt. Such an impact melt would have to be rapidly quenched before the silicates could completely separate from metal and then strongly metamorphosed.

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