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# Petrology and chemistry of the basaltic shergottite North West Africa 480

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**Abstract**–North West Africa (NWA) 480 is a new martian meteorite of 28 g found in the Moroccan Sahara in November 2000. It consists mainly of large gray pyroxene crystals (the largest grains are up to 5 mm in length) and plagioclase converted to maskelynite. Excluding the melt pocket areas, modal analyses indicate the following mineral proportions: 72 vol% pyroxenes extensively zoned, 25% maskelynite, 1% phosphates (merrillite and chlorapatite), 1% opaque oxides (ilmenite, ulvöspinel and chromite) and sulfides, and 1% others such as silica and fayalite. The compositional trend of NWA 480 pyroxenes is similar to that of Queen Alexandra Range (QUE) 94201 but in NWA 480 the pyroxene cores are more Mg-rich ($En_{77}$-$En_{65}$). Maskelynites display a limited zoning ($An_{42-50}Ab_{54-48}Or_{2-4}$). Our observations suggest that NWA 480 formed from a melt with a low nuclei density at a slow cooling rate. The texture was achieved *via* a single-stage cooling where pyroxenes grew continuously. A similar model was previously proposed for QUE 94201 by McSween *et al.* (1996). NWA 480 is an Al-poor ferroan basaltic rock and resembles Zagami or Shergotty for major elements and compatible trace element abundances. The bulk rock analysis for oxygen isotopes yields $\Delta^{17}O = +0.42‰$, a value in agreement at the high margin, with those measured on other shergottites (Clayton and Mayeda, 1996; Romanek *et al.*, 1998; Franchi *et al.*, 1999). Its CI-normalized rare earth element pattern is similar to those of peridotitic shergottites such as Allan Hills (ALH)A77005, suggesting that these shergottites shared a similar parent liquid, or at least the same mantle source.

## INTRODUCTION

The shergottites, nakhlites, Chassigny and Allan Hills (ALH) 84001 are igneous rocks believed to have originated on Mars (*e.g.*, McSween, 1994; Treiman *et al.*, 2000). They are among the most studied meteorites because, in the absence of returned martian samples, they provide direct insights into the differentiation and magmatic history of the red planet. A few of the so-called "martian meteorites" are old cumulate rocks, such as ALH 84001 (~4.5 Ga) and the nakhlites (~1.3 Ga). The shergottites are younger, and demonstrate that Mars was still active 170 Ma ago. Three types of shergottites were described (McSween and Treiman, 1998): peridotitic shergottites, all collected in Antarctica, are interpreted as olivine and pyroxene cumulates possibly formed at depth; picritic and basaltic shergottites are surface (or subsurface) products, and are less affected by crystal accumulation processes.

A new basaltic shergottite of 28 g (Fig. 1) was found in November 2000 in the Moroccan Sahara by a meteorite hunter and is named North West Africa (NWA) 480. A first 1.7 g fragment was given for its characterization and its martian origin was established (Barrat *et al.*, 2001a). Subsequently, the main mass was acquired by the Centre National d'Etudes Spatiales (CNES) and given to the Centre National de la Recherche Scientifique (CNRS) for its complete study *via* a consortium (Consortium Théodore Monod). In this paper, we present a petrological and chemical study of NWA 480 and provide a comparison with other shergottites.

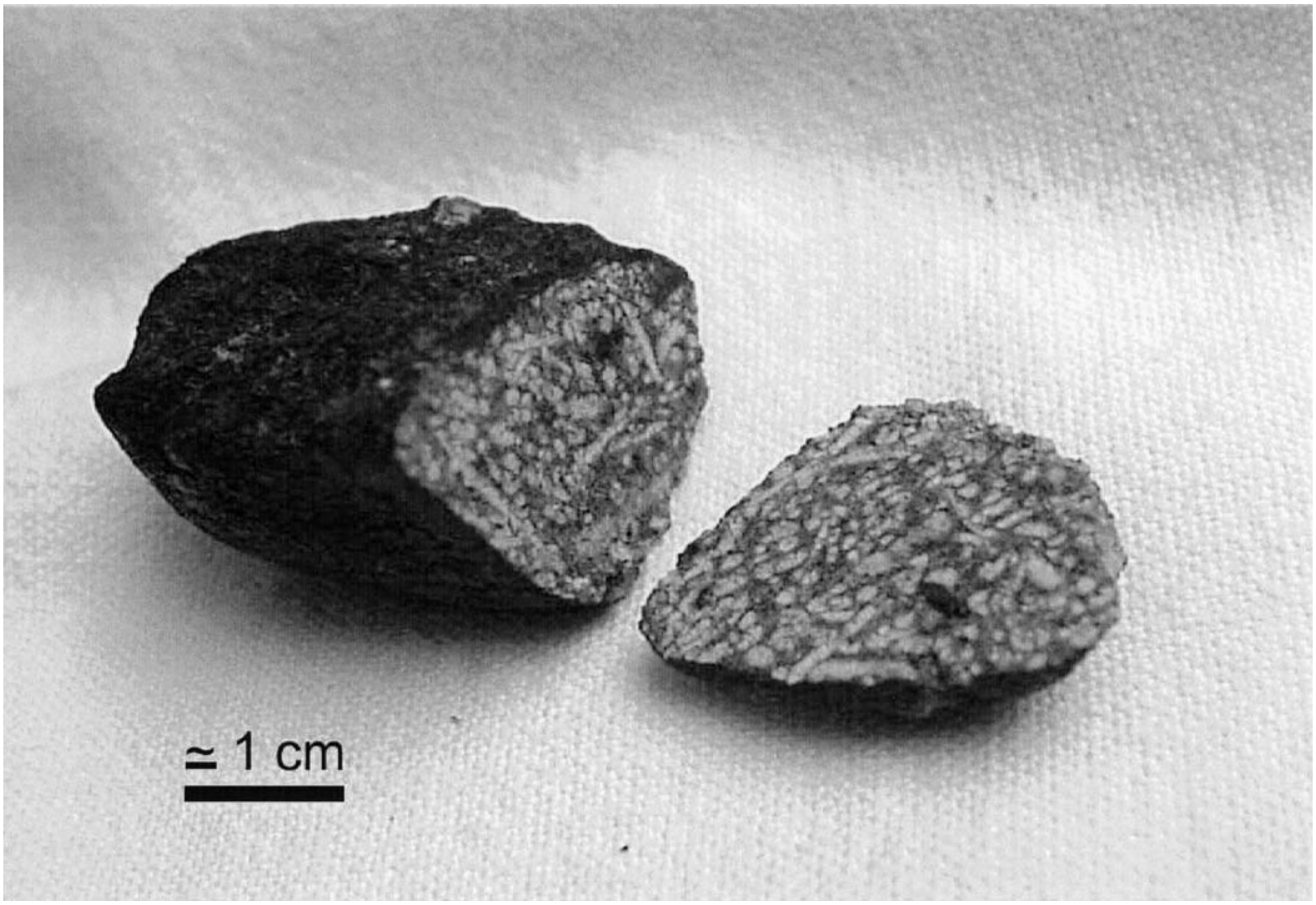


FIG. 1. The main mass of NWA 480 (picture courtesy of B. Fectay and C. Bidaut).

## ANALYTICAL METHODS

Petrographic observations and quantitative chemical analyses of the various phases were made on a polished section of NWA 480. Backscattered electron (BSE) images were taken with a JEOL JSM6301-F scanning electron microscope (SEM) with an energy dispersive spectrometer (EDS) (SCIAM, Angers). Cameca SX50 electron microprobe analyses at the Université de Paris VI were generally obtained at 15 kV accelerating voltage with a sample current of 12 nA. For maskelynite analysis, we used a defocused beam of 10 $\mu$m in diameter and a sample current of 8 nA as suggested by Mikouchi *et al.* (1999), in order to minimize volatile loss.

Major and trace element concentrations were determined, respectively, by inductively coupled plasma-atomic emission spectrometry (ICP-AES) and inductively coupled plasma-mass spectrometry (ICP-MS) in Grenoble using the procedure described by Barrat *et al.* (2000). The accuracy on major and trace element concentrations is better than 5% (probably better than 3% for all the rare earth elements (REEs)) based on various standard and sample duplicates.

The modal composition has been estimated from points counted on BSE images, Ca and Mg images, and finally from the mineral phases and bulk-rock compositions.

Oxygen isotopes were determined by laser fluorination at the Institut de Physique du Globe de Paris: ~1 mg aliquots are oxidized in a 100 mbar $BrF_5$ atmosphere in a $CO_2$ Melles Griot laser beam. The resulting oxygen is purified over a KBr furnace and analyzed as $O_2$ in a VG Optima dual inlet mass spectrometer. Quartz and tholeiitic glass secondary standards are routinely run in the $BrF_5$ chamber together with the meteoritic samples.

## RESULTS AND DISCUSSION

### Petrography and Mineral Compositions

This small stone (28 g) is nearly totally covered with black fusion crust. It is extremely fresh and weathering products (such as carbonates) are limited to a few spots on the glassy surface. On the sawn surface, the interior is coarse-grained crystalline and consists mainly of large gray pyroxene crystals (the largest grains are up to 3 mm in length) and plagioclase converted to maskelynite (Fig. 1). This gabbroic rock resembles Los Angeles, another coarse-grained shergottite recently described (Rubin *et al.*, 2000), but it is clearly richer in pyroxenes like Shergotty and Zagami (*e.g.*, Stolper and McSween, 1979; Mikouchi *et al.*, 1999).

Excluding the melt pocket areas, modal analyses indicate the following mineral proportions: 72 vol% pyroxenes, 25% maskelynite, 1% phosphates (merrillite and chlorapatite), 1% opaque oxides (mainly ilmenite and chromite) and sulfides, and 1% others such as silica and fayalite. Representative analyses of the mineral phases are given in Tables 1 and 2.

**Pyroxenes**–Pyroxenes are subhedral to euhedral and display a very complex zoning (Figs. 2 to 4). Their FeO/MnO ratios (FeO/MnO = 36, $n$ = 170) are similar to those in other martian basalts (*e.g.*, McSween and Treiman, 1998). Their cores are Mg-rich ($En_{77}Fs_{20}Wo_3$-$En_{65}Fs_{29}Wo_6$, 15% of the rock volume), surrounded by Mg-rich augite (typically $En_{41}Fs_{29}Wo_{30}$, 31 vol%), and finally zoned toward a pigeonitic rim (~26 vol%) sometimes with a nearly Mg-free composition

TABLE 1. Representative electron microprobe analyses of pyroxenes of NWA 480 (in wt%).

| # | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Cr_2O_3$ | FeO* | MnO | MgO | CaO | $Na_2O$ | Total | En | Wo | Fs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low-Ca pyroxene cores** | | | | | | | | | | | | | |
| A | 55.44 | 0.04 | 0.31 | 0.52 | 13.22 | 0.38 | 28.41 | 1.42 | 0.02 | 99.75 | *77.1* | *2.8* | *20.1* |
| B | 55.23 | 0.08 | 0.31 | 0.54 | 14.54 | 0.37 | 26.78 | 1.59 | 0.03 | 99.47 | *74.2* | *3.2* | *22.6* |
| C | 55.03 | 0.10 | 0.33 | 0.44 | 15.95 | 0.50 | 25.47 | 2.07 | 0.05 | 99.94 | *70.9* | *4.1* | *24.9* |
| D | 54.00 | 0.10 | 0.43 | 0.50 | 18.17 | 0.62 | 22.88 | 2.92 | 0.05 | 99.66 | *65.1* | *6.0* | *29.0* |
| **Augite** | | | | | | | | | | | | | |
| E | 52.30 | 0.29 | 0.90 | 0.72 | 14.61 | 0.53 | 15.11 | 14.38 | 0.17 | 99.01 | *44.9* | *30.7* | *24.4* |
| F | 51.98 | 0.31 | 1.08 | 0.78 | 15.39 | 0.58 | 14.77 | 14.60 | 0.19 | 99.66 | *43.6* | *31.0* | *25.5* |
| G | 50.12 | 0.49 | 1.39 | 0.57 | 18.79 | 0.53 | 12.57 | 14.34 | 0.16 | 98.96 | *37.6* | *30.8* | *31.5* |
| **Fe-pigeonite** | | | | | | | | | | | | | |
| H | 50.38 | 0.51 | 0.91 | 0.36 | 25.66 | 0.82 | 12.88 | 7.69 | 0.07 | 99.29 | *39.3* | *16.9* | *43.9* |
| I | 48.63 | 0.54 | 0.62 | 0.20 | 31.29 | 0.87 | 8.61 | 8.34 | 0.09 | 99.19 | *26.8* | *18.6* | *54.6* |
| J | 46.87 | 0.72 | 0.52 | 0.04 | 38.17 | 0.89 | 3.82 | 7.58 | 0.05 | 98.67 | *12.5* | *17.8* | *69.8* |
| K | 46.85 | 0.53 | 0.34 | 0.01 | 41.43 | 1.01 | 3.19 | 6.54 | 0.03 | 99.93 | *10.3* | *15.1* | *74.6* |
| L | 46.44 | 0.56 | 0.39 | 0.00 | 41.17 | 1.02 | 2.77 | 6.82 | 0.08 | 99.24 | *9.0* | *15.9* | *75.1* |
| M | 46.16 | 0.53 | 0.37 | 0.00 | 42.89 | 1.02 | 1.89 | 6.09 | 0.05 | 99.00 | *6.2* | *14.4* | *79.4* |
| N | 45.26 | 0.52 | 0.43 | 0.00 | 43.56 | 0.81 | 1.81 | 5.98 | 0.04 | 98.40 | *5.9* | *14.1* | *80.0* |

TABLE 2. Representative electron microprobe analyses of maskelynite, silica, phosphates and oxides of NWA 480 (in wt%).

| | Maskelynite | | Silica | Apatite | Merrillite | Ilmenite | Chromite |
|---|---|---|---|---|---|---|---|
| | core | rim | $n = 2$ | $n = 8$ | $n = 4$ | $n = 4$ | $n = 3$ |
| $SiO_2$ | 55.81 | 58.06 | 97.40 | 0.83 | 0.10 | 0.03 | 0.08 |
| $TiO_2$ | 0.06 | 0.09 | 0.27 | 0.10 | 0.02 | 50.40 | 1.17 |
| $Al_2O_3$ | 27.15 | 26.14 | 2.13 | 0.01 | 0.02 | 0.11 | 4.73 |
| $Cr_2O_3$ | – | – | 0.00 | 0.01 | 0.01 | 0.02 | 58.91 |
| FeO | 0.70 | 0.76 | 0.21 | 1.55 | 5.20 | 46.39 | 30.38 |
| MnO | 0.00 | 0.00 | 0.00 | 0.15 | 0.11 | 0.69 | 0.45 |
| MgO | 0.07 | 0.04 | 0.00 | 0.02 | 0.84 | 0.12 | 2.74 |
| CaO | 10.04 | 8.79 | 0.24 | 52.96 | 47.73 | 0.04 | 0.03 |
| $Na_2O$ | 5.32 | 6.19 | 0.40 | 0.11 | 0.66 | 0.02 | 0.01 |
| $K_2O$ | 0.37 | 0.54 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| $P_2O_5$ | – | – | 0.00 | 41.84 | 45.40 | 0.00 | 0.00 |
| NiO | – | – | 0.00 | 0.00 | 0.03 | 0.03 | 0.03 |
| F | – | – | – | 1.54 | – | – | – |
| Cl | – | – | – | 2.04 | – | – | – |
| Total | 99.52 | 100.61 | 100.66 | 101.16 | 100.13 | 97.85 | 98.54 |

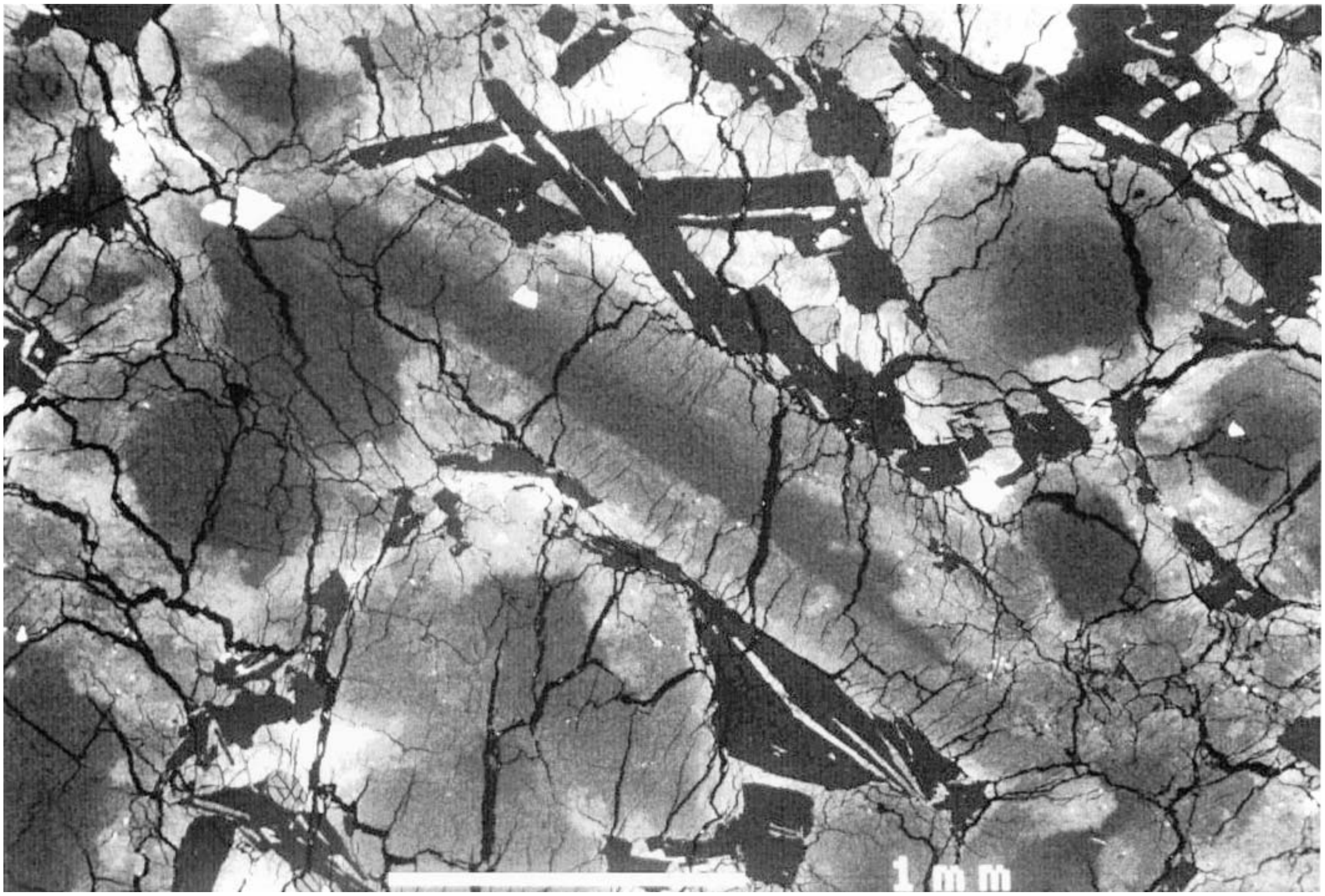


FIG. 2. Backscattered electron image of a polished section of NWA 480. Large gray crystals are zoned pyroxene, and dark phase is maskelynite. Fe-Ti oxides, pyrrhotite, and chromite appear white.

($En_5Fs_{84}Wo_{11}$). Pyroxferroite (or its breakdown products) has not been detected yet. The augite bands seem "ragged" and their thicknesses are irregular as shown in a BSE image or in a compositional profile (Figs. 2 and 3). In some places, augite is lacking and Mg-rich cores and Fe-rich pigeonite are directly in contact. Similar features were extensively described in another basaltic shergottite Queen Alexandra Range (QUE) 94201 (McSween *et al.*, 1996; Mikouchi *et al.*, 1998, 1999) but the range of compositions displayed by the NWA 480 pyroxenes is among the largest described so far for a basaltic shergottite and their cores are among the most magnesian analyzed yet: their compositions overlap those of orthopyroxene crystals found in Dar al Gani 476/489/670 basaltic shergottite ($En_{83-71}$; Zipfel *et al.*, 2000; Folco *et al.*, 2000; Folco and Franchi, 2000; Mikouchi *et al.*, 2001) or those of peridotitic shergottites ($En_{78-65}$; McSween and Treiman, 1998). It is unclear whether the NWA 480 phenocryst cores are orthorhombic or not and its dominant constituent polymorph is yet to be determined.

Minor elements are also zoned from core to rim (Fig. 3) and their variations relative to the atomic Fe/(Fe + Mg) ratio are shown in Fig. 5. Aluminum, Cr and Na display the same behavior. Their concentrations increase from core to the Mg-rich augite band then decrease in the Fe-rich pigeonite rim. $TiO_2$ abundances increase continuously from core to rim. The same minor element trends in pyroxenes are known in other basaltic shergottites such as Elephant Moraine (EET)A79001B and QUE 94201, but in the latter, augite areas tend to be richer in $Al_2O_3$ than in NWA 480, with concentrations often reaching 1.5% (Mikouchi *et al.*, 1998, 1999).

We tentatively examined the NWA 480 pyroxenes at high magnification by field emission gun-scanning electron microscopy in order to detect exsolution features. Most pyroxenes are devoid of exsolution at least on the scale of a few tens of nanometers. We find no evidence of exsolution in the Mg-rich cores and in the augite bands. The only exsolutions bearing-area we have observed (Fig. 6), is located in a Fe-pigeonite in contact with a small melt pocket.

**Maskelynites**–All the plagioclase has been converted by shock into maskelynite as in other basaltic shergottites. They are interstitial to pyroxenes and typically lath-shaped. They display small offshoots (occurring as smooth and irregular branches in the neighboring pyroxenes) and sometimes contain

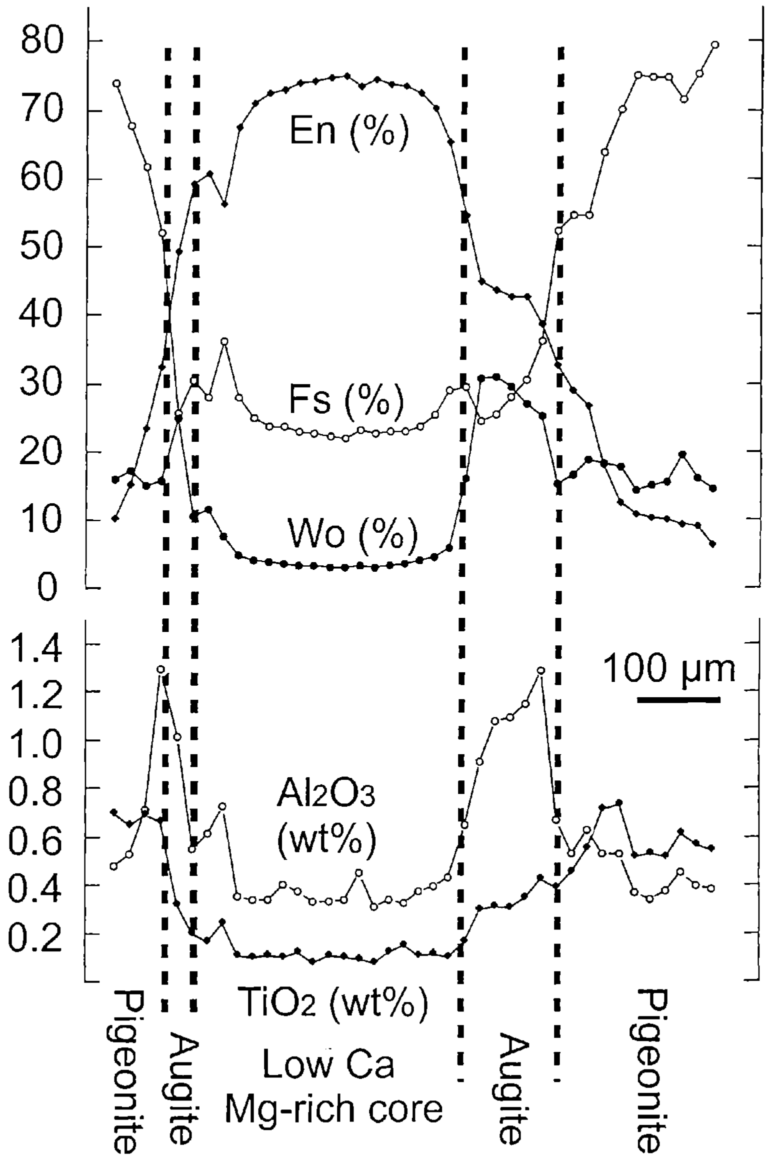


FIG. 3. Chemical zoning of a NWA 480 pyroxene.

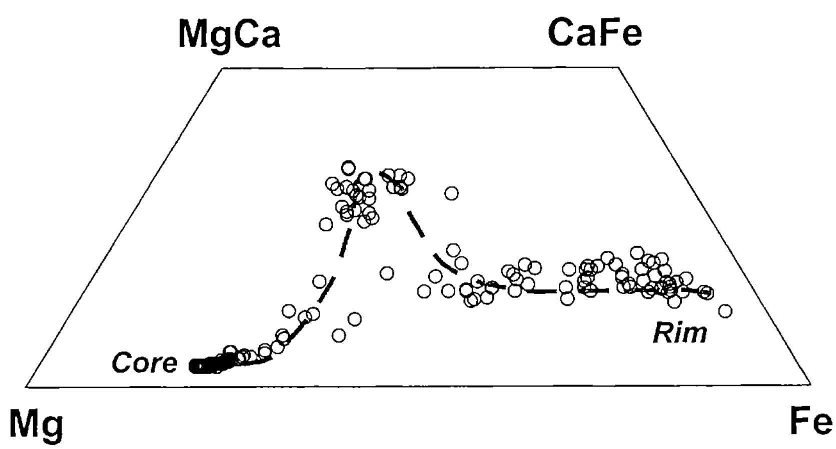


FIG. 4. Quadrilateral pyroxene composition of NWA 480.

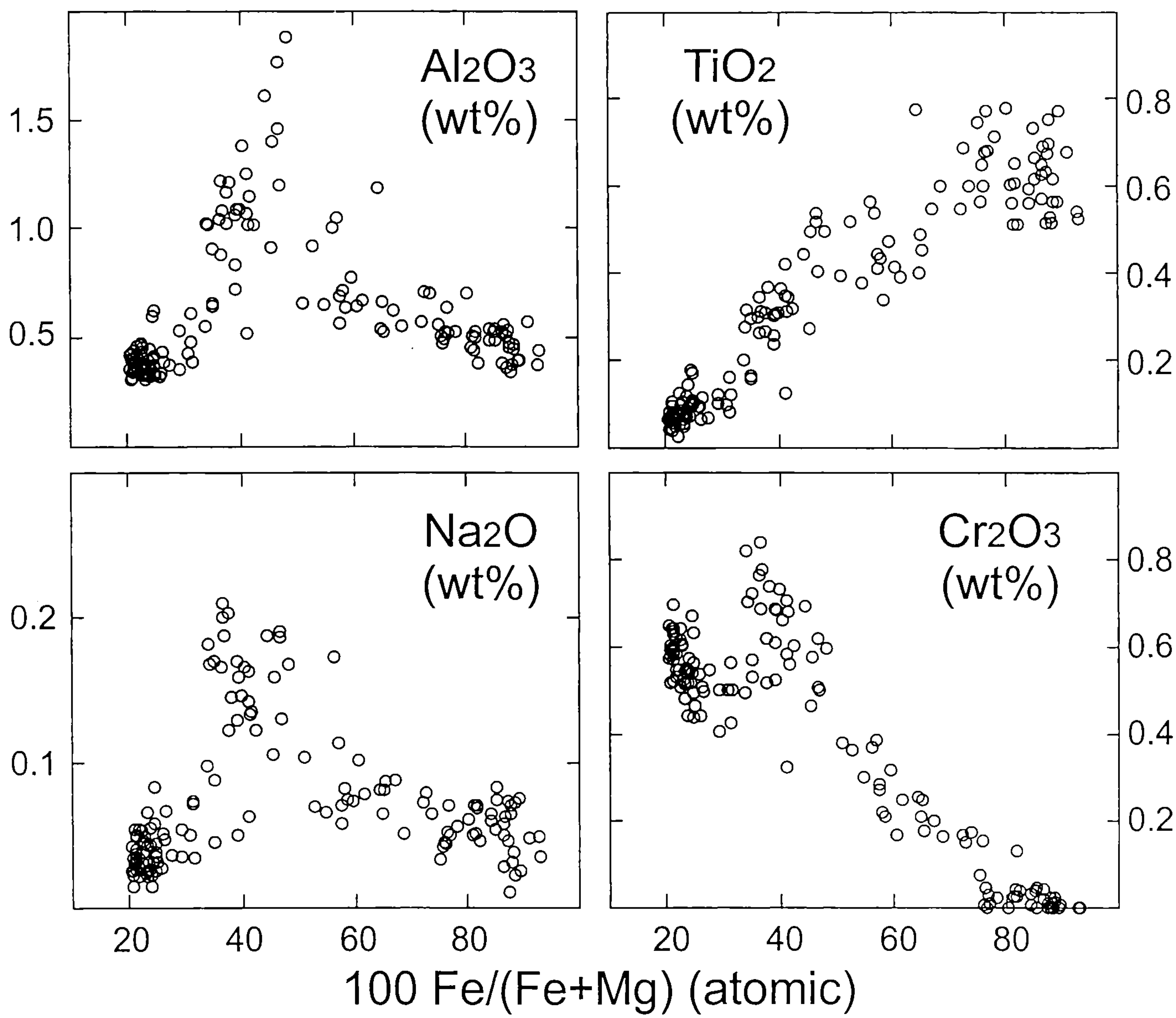


FIG. 5. Variations of $Al_2O_3$, $TiO_2$, $Na_2O$, $Cr_2O_3$, and in pyroxenes from NWA 480 relative to atomic Fe/(Fe + Mg).

pyroxene fragments which separated from the border and drifted into the maskelynite. The grains display a limited normal zoning ($An_{42-50}Ab_{54-48}Or_{2-4}$). They contain a significant amount of Fe (FeO* = 0.5–1.1 wt%). These concentrations are very similar to the values already reported for the Shergotty maskelynites (Hale *et al.*, 1999).

**Phosphates**–Merrillite and chlorapatite are present in NWA 480. Merrillite, which is the most abundant, occurs as rounded interstitial grains (the largest is up to 0.1 mm in length) and contains a significant amount of FeO (~5 wt%). Merrillite grains are often rimmed by a 6–40 $\mu$m thick mixture of fayalite (~$Fa_{95}$), a silica rich phase (silica or a silica rich-glass?), accessory Fe-Ti oxides and pyrrhotite (Fig. 7). These intergrowths suggest that the late stages of crystallization occurred at an oxygen fugacity close to the FMQ buffer. Such rims were not observed around chlorapatite. Similar intergrowths have been described in Zagami (McCoy *et al.*, 1999).

**Opaque Minerals**–Chromite crystals are found in the pyroxene cores. Ilmenite occurs as interstitial crystals in close association with sulfides, ulvöspinel, fayalite (~$Fa_{95}$) and merrillite. Ulvöspinel contains fine ilmenite lamellae (<1 $\mu$m thick) parallel to three directions which indicate subsolidus equilibration (Fig. 8).

**Silica**–Silica occurs mostly as irregular grains included in maskelynite or between maskelynite and pyroxene, typically surrounded by radiating cracks. It resembles the silica grains recently described in Shergotty by Sharp *et al.* (1999). Electron microprobe analyses show that this phase contains minor

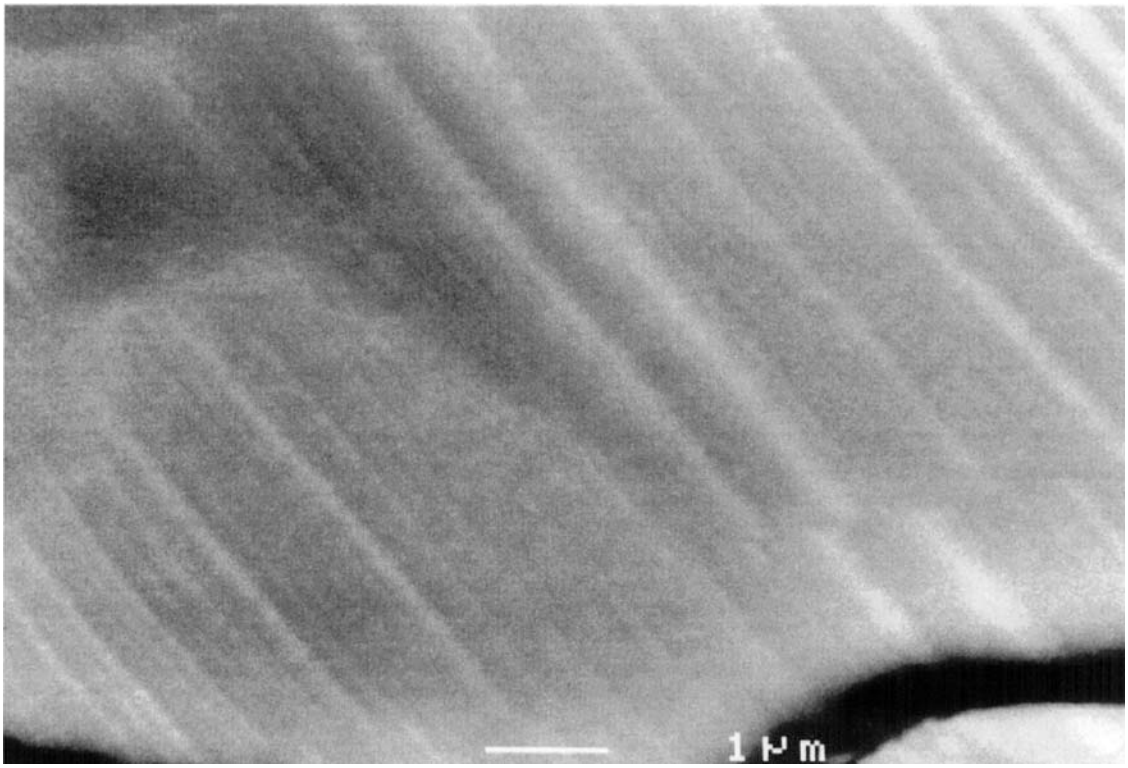


FIG. 6. Backscattered electron image of a pyroxene displaying thin exsolutions.

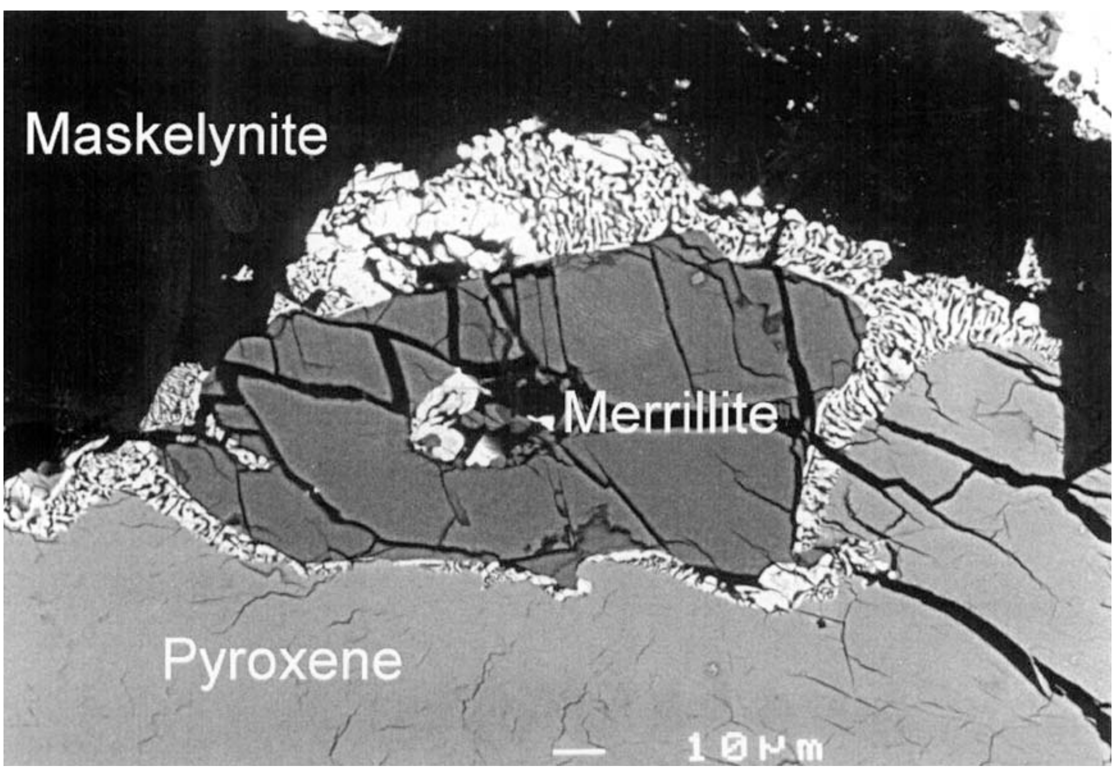


FIG. 7. Backscattered electron image of merrillite crystal rimmed by a fayalite-silica rich phase intergrowth.

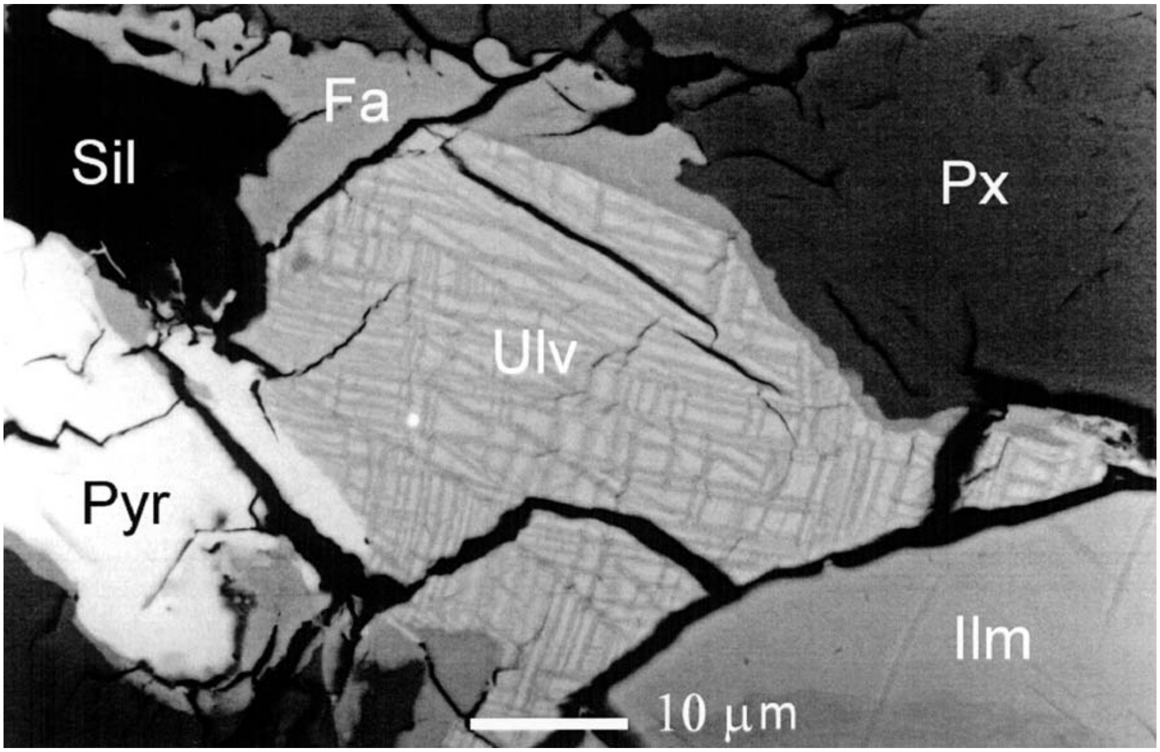


FIG. 8. Backscattered electron image of an ulvöspinel crystal displaying thin ilmenite exsolutions. The crystal (Ulv) is in contact with a larger ilmenite crystal (Ilm), fayalite (Fa), pyroxene (Px), pyrrothite (Pyr), merrillite and a silica-rich phase (dark area Sil).

amounts of $Al_2O_3$ (~2 wt%) and $Na_2O$ (~0.4 wt%) like the silica grains in Shergotty (Stolper and McSween, 1979; Sharp *et al.*, 1999) and Zagami (Weber *et al.*, 2000). Raman spectroscopy measurements show that these silica grains represent a mixture of dense silica glass and stishovite. Additionally, stishovite needles and grains were recognized in the impact melt pockets. A detailed mineralogical study of these pockets and silica phases is in progress (Gillet *et al.*, unpubl. data).

**Crystallization History of North West Africa 480**

The NWA 480 and QUE 94201 pyroxenes display striking resemblances suggesting that the cooling histories of these two shergottites are similar. In both cases, the pyroxenes consist of a low-Ca core successively rimmed by irregular augite bands, followed by Fe-pigeonite. As for QUE 94201 (McSween *et al.*, 1996; Wadhwa *et al.*, 1998; Mikouchi *et al.*, 1998, 1999), major and minor element compositions of pyroxenes in NWA 480 show a continuum of compositions suggesting that the phases grew in a fractionating, closed-system. Hence, petrographic observations and minor element behavior in pyroxenes can be used to propose a crystallization sequence of NWA 480 (Fig. 9).

Low-Ca Mg-rich pyroxene and chromite (which occurs only in the pyroxene cores) were the first phases to crystallize. These Mg-rich pyroxenes served as nucleation sites for augite and Fe-rich pigeonite. Decreases in Al and Na abundances in pyroxenes are correlated with the transition augite/Fe-pigeonite (Figs. 3 and 5), and mark the onset of plagioclase crystallization. This interpretation is in agreement with petrographic observations because maskelynite was never observed in contact with Mg-rich pyroxenes or crossing the augite bands in our polished section. Wadhwa *et al.* (1998) have suggested that phosphates appeared after augite and before Fe-pigeonite during the crystallization of QUE 94201. The preliminary trace element abundances in NWA 480 pyroxenes obtained by Crozaz *et al.* (2001) indicate the same history. Moreover, we suggest that chlorapatite appeared before merrillite in NWA 480 because chlorapatite is not rimmed by very late phase overgrowths whereas merrillite often is. The late crystallization phases were Fe-Ti oxides, pyrrhotite, fayalite and a silica-rich phase.

The origin of pyroxene zoning in shergottites has been extensively discussed. It may be indicative of a multistage magmatic history with Mg-rich pyroxene crystallization in a deep-seated (1–2 kbar) magma chamber followed by eruption of a thick phenocryst-bearing lava flow, as suggested for Shergotty and Zagami (Stolper and McSween, 1979; McCoy *et al.*, 1992; McSween *et al.*, 2001). Mikouchi *et al.* (1998, 1999) have proposed that undercooling is chiefly responsible in producing the QUE 94201 pyroxene zoning. They suggest

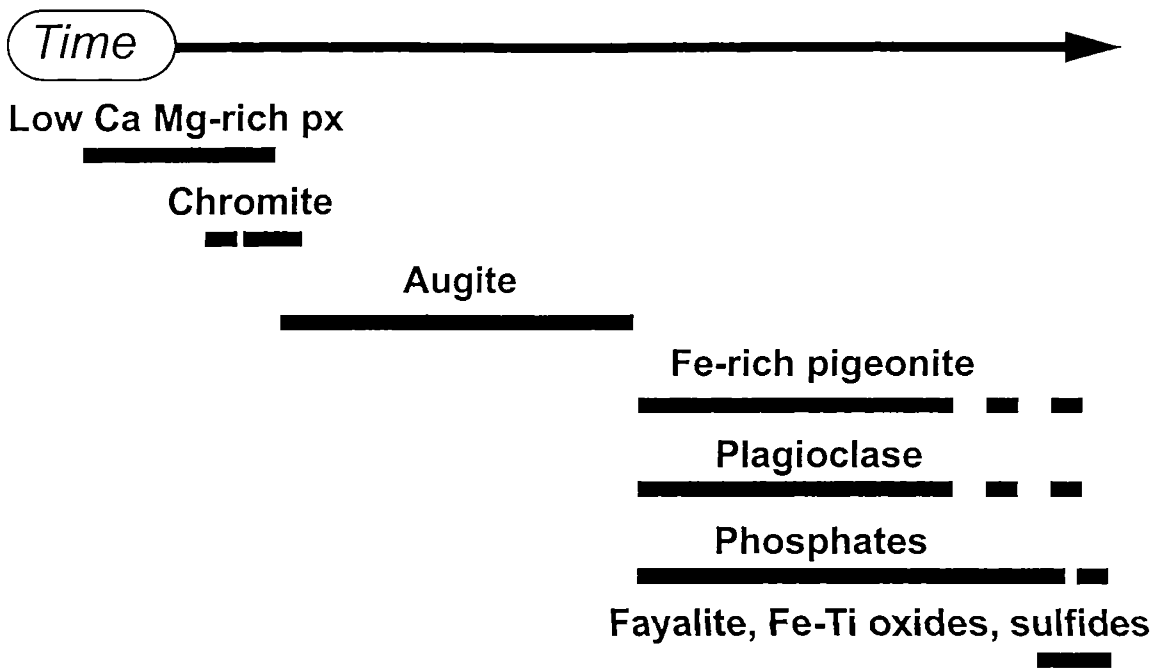


FIG. 9. The crystallization sequence in NWA 480. Bars represent appearance and disappearance of various phases. The timescale is arbitrary (and probably not linear).

that the crystallization sequence of this basaltic shergottite was pigeonite, augite, plagioclase and Fe-rich pigeonite, with each phase crystallizing metastably alone. Though such a hypothesis is able to explain the original zoning of shergottitic pyroxenes, we do not favor it since it requires unnecessarily complex physical conditions. Controlled linear cooling-rate experiments at a rate of ~0.5 °C/h have reproduced a similar pyroxene zoning using lunar basalt compositions (Lofgren *et al.*, 1974; Grove and Bence, 1977). These results were used by McSween *et al.* (1996) to propose that the QUE 94201 texture was achieved *via* a single-stage cooling where pyroxenes grew continuously. The same line of evidence may be used for NWA 480 and we suggest that the NWA 480 texture formed from a melt with a low nuclei density at a similarly slow cooling rate. This interpretation is in agreement with the few available dynamic crystallization experiments carried out on shergottitic melts (McCoy and Lofgren, 1999).

**Bulk Chemistry**

The compositions of the fusion crust and of an interior fragment weighing 182.2 mg are given in Table 3. These analyses are similar in term of major element concentrations. NWA 480 is an Al-poor ferroan basaltic rock and resembles Zagami or Shergotty. Because hot desert alteration is able to significantly affect the composition of meteorites (*e.g.*, Barrat *et al.*, 1999, 2001b; Stelzner *et al.*, 1999; Zipfel *et al.*, 2000; Crozaz and Wadhwa, 2001), the effects of weathering are evaluated here first. The lack of evidence of terrestrial alteration is illustrated by the U, Ba and Sr abundances which are sensitive indicators of surface processes: NWA 480 displays a normal Th/U ratio and its Ba and Sr abundances are not outside the trend defined by other unweathered shergottites (Fig. 10). Hence, our analyses allow us to address the nature of the parent body and the genesis of NWA 480.

Many diagrams or element ratios have been used in order to discriminate the various types of basaltic achondrites (*e.g.*, Treiman *et al.*, 2000). Key element ratios such as FeO*/MnO (~40), Na/Al (~0.3), K/La (= 560) or Ga/Al (= $4.8 \times 10^{-4}$) indicate that NWA 480 is a new member of the martian meteorites clan. This conclusion is confirmed by the bulk rock analysis for oxygen isotopes (Table 3) which yields $\Delta^{17}O$ = +0.42‰, a value in agreement at the high margin, with those measured on other shergottites (Clayton and Mayeda, 1996; Romanek *et al.*, 1998; Franchi *et al.*, 1999).

Compared to other basaltic shergottites, NWA 480 displays Al and compatible element abundances (such as Ni, Co, Cr, Cu) close to those of Shergotty and Zagami (*e.g.*, Fig. 11). However, differences are obvious when incompatible elements such as the REEs are taken into account (Fig. 12). The NWA 480 CI-normalized pattern is typical of shergottites. It is enriched from Lu to Eu (with no anomaly), depleted from Eu to Pr, and slightly upturned toward La. NWA 480 contains about the same amounts of La and Yb than Zagami (about 6–7 × CI), but it is twice as rich in Eu. It is more light REE depleted than Zagami (or Shergotty, not shown) but less than EETA79001B. Surprisingly, the NWA 480 pattern is similar to those of peridotitic shergottites such as ALHA77005. We suspect that these shergottites shared a similar parent liquid, or at least the

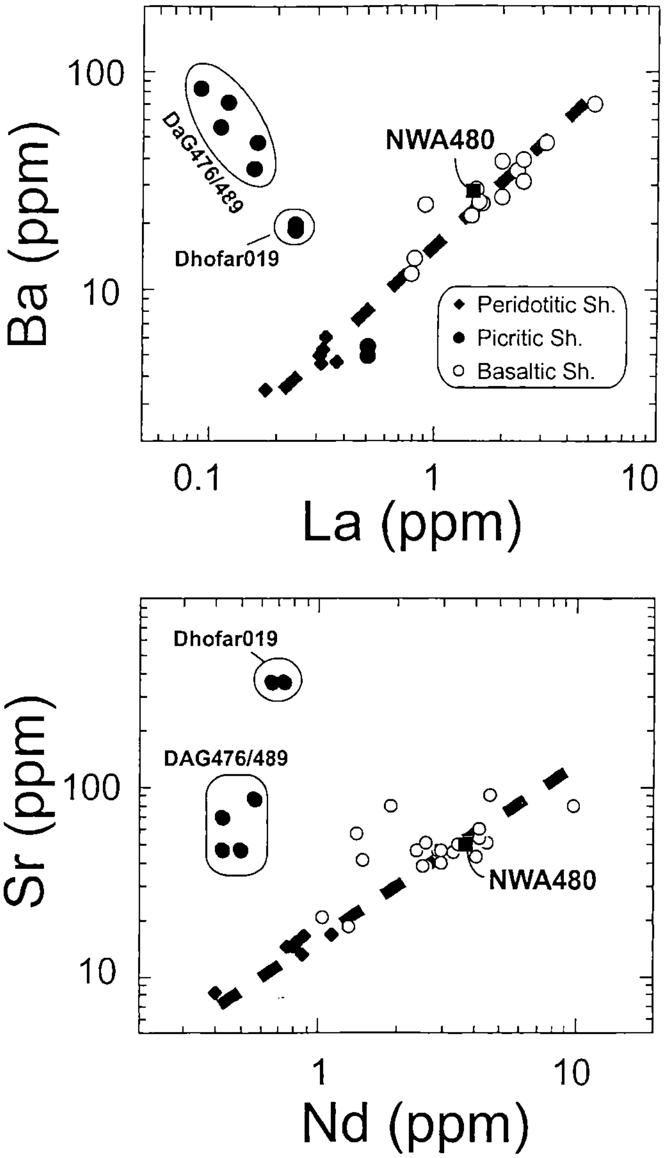


FIG. 10. Ba *vs.* La and Sr *vs.* Nd for shergottites. Unlike NWA 480, Dhofar 019 and Dar al Gani 476/489 display a strong Ba and Sr enrichment, a feature of hot desert weathering. Literature data are from Barrat *et al.* (2001b), Borg *et al.* (1997), Burghele *et al.* (1983), Dreibus *et al.* (1982, 1992, 1996, 2000), Folco *et al.* (2000), Gleason *et al.* (1997), Jagoutz (1989), Jagoutz and Wänke (1986), Jérome (1970), Kong *et al.* (1999), Laul *et al.* (1986), Ma *et al.* (1981, 1982), Neal *et al.* (2001), Rubin *et al.* (2000), Shih *et al.* (1982), Smith *et al.* (1984), Treiman *et al.* (1994), Warren and Kallemeyn (1987, 1996), Warren *et al.* (1999), and Zipfel *et al.* (2000).

TABLE 3. Major and trace element abundances for shergottite NWA 480 (oxides in wt%, trace elements in ppm).

| | Fusion crust (EMPA) | Bulk sample (ICP-AES) | | Bulk sample (ICP-MS) |
|---|---|---|---|---|
| $SiO_2$ | 51.1 | – | Li | 2.93 |
| $TiO_2$ | 1.09 | 1.16 | Be | 0.21 |
| $Al_2O_3$ | 5.00 | 6.46 | Sc | 28 |
| $Cr_2O_3$ | 0.28 | 0.31 | V | 202 |
| FeO* | 21.63 | 19.44 | Co | 37.6 |
| MnO | 0.51 | 0.51 | Ni | 63 |
| MgO | 9.92 | 10.06 | Cu | 17.6 |
| CaO | 8.35 | 9.32 | Zn | 64 |
| $Na_2O$ | 1.26 | 1.26 | Ga | 16.27 |
| $K_2O$ | 0.30 | 0.10 | Rb | 2.67 |
| $P_2O_5$ | 0.53 | – | Sr | 49.3 |
| Total | 99.97 | – | Y | 16.46 |
| | | | Zr | 58.74 |
| | | | Nb | 1.99 |
| FeO*/MnO | 42.41 | 38.12 | Cs | 0.19 |
| FeO*/MgO | 2.18 | 1.93 | Ba | 28.40 |
| Na/Al | 0.35 | 0.27 | La | 1.48 |
| Na/Ti | 1.43 | 1.34 | Ce | 3.77 |
| | | | Pr | 0.619 |
| | | | Nd | 3.70 |
| | | | Sm | 1.73 |
| Ga/Al | – | $4.75 \times 10^{-4}$ | Eu | 0.756 |
| Th/U | – | 3.34 | Gd | 2.67 |
| Zr/Hf | – | 35.9 | Tb | 0.477 |
| Lu/Hf | – | 0.12 | Dy | 3.05 |
| K/La | – | 560 | Ho | 0.620 |
| $(La/Sm)_n$ | – | 0.54 | Er | 1.57 |
| Eu/Eu* | – | 1.08 | Yb | 1.33 |
| | | | Lu | 0.190 |
| | | | Hf | 1.64 |
| | | | Ta | 0.10 |
| $\delta^{18}O$ (‰) | – | +4.78 | W | 0.34 |
| $\delta^{17}O$ (‰) | – | +2.91 | Pb | 0.37 |
| $\Delta^{17}O$ (‰) | – | +0.42 | Th | 0.215 |
| | | | U | 0.064 |

same mantle source. Isotope studies are now required to determine the age of NWA 480 and to discuss its possible petrogenetic link with peridotitic shergottites (Göpel *et al.*, unpubl. data).

## SUMMARY

We have documented the petrology, major and trace geochemistry and oxygen isotopic composition of NWA 480, a new find from Moroccan Sahara. Our data demonstrate that this small meteorite is a new basaltic shergottite. It is a coarse-grained rock consisting mainly of large zoned pyroxenes and maskelynitized plagioclases. In terms of texture, pyroxene zoning and crystallization sequence, it resembles QUE 94201 despite the fact that the mode and composition of the phases are different. Chemically, the bulk composition of NWA 480 is close to those of Zagami or Shergotty for major elements or compatible trace elements (such as Ni, Co, Cr, Cu) but its incompatible trace element features are unlike those of all the other known basaltic shergottites. Surprisingly, its REE pattern is very similar to those of the peridotitic shergottites, such as ALHA77005,

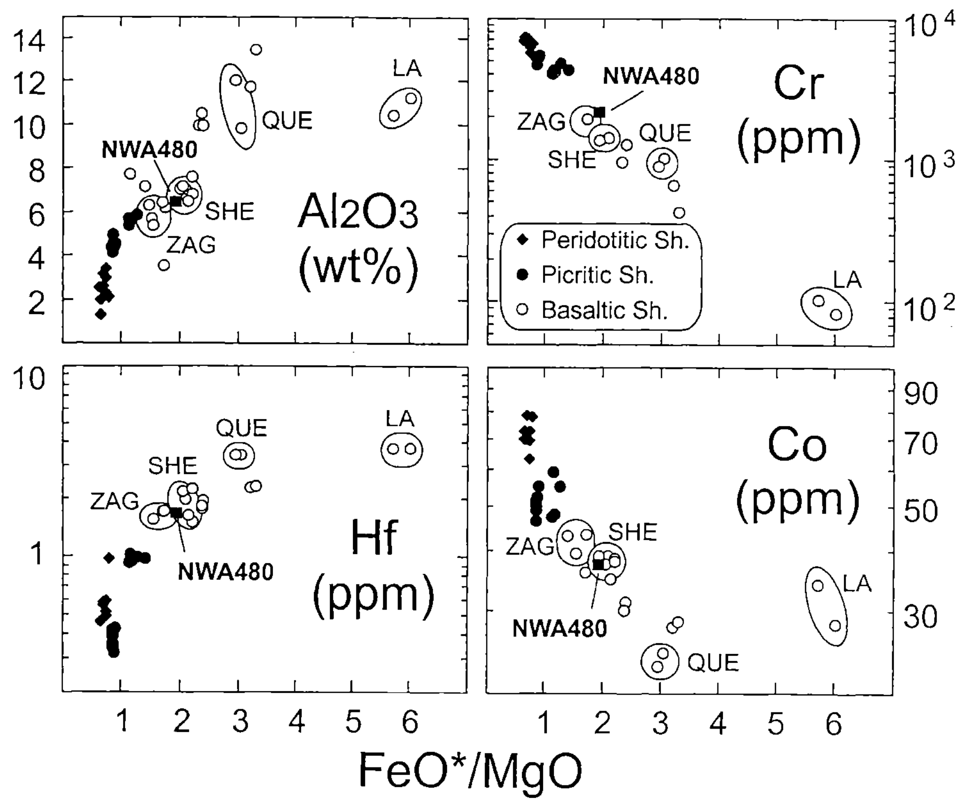


FIG. 11. $Al_2O_3$, Cr, Hf, and Co *vs.* FeO*/MgO for shergottites (ZAG = Zagami; SHE = Shergotty; QUE = QUE 94201; LA = Los Angeles). See Fig. 10 for data source.

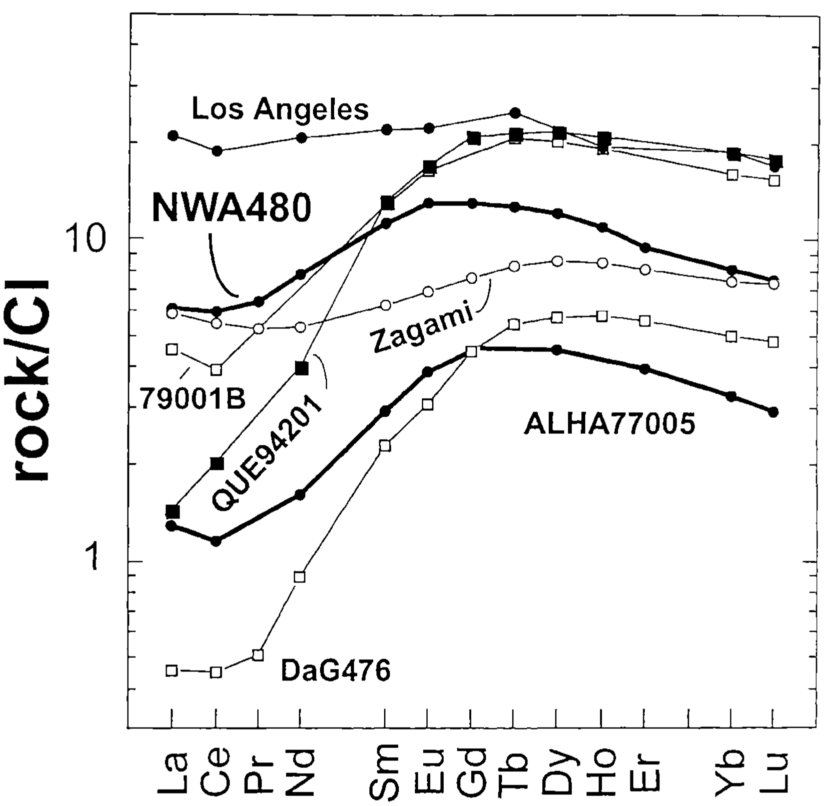


FIG. 12. REE patterns of NWA 480 and representative shergottites. The reference chondrite is from Evensen *et al.* (1978). The literature data are from Shih *et al.* (1982), Dreibus *et al.* (1996), Warren *et al.* (1999), and Barrat *et al.* (2001b).

suggesting that these shergottites shared a similar parent liquid, or at least the same mantle source.

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