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Northwest Africa 2526: A partial melt residue of enstatite chondrite parentage

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Abstract–NWA 2526 is a coarse-grained, achondritic rock dominated by equigranular grains of polysynthetically twinned enstatite (~85 vol%) with frequent 120° triple junctions and ~10–15 vol% of kamacite + terrestrial weathering products. All other phases including troilite, daubreelite, schreibersite, and silica-normative melt areas make up <~1 vol% of the rock. Oxygen isotopic analyses are well within the range of those for enstatite chondrites and aubrites. We show that the "enstatite achondrite" (Russell et al. 2005) Northwest Africa (NWA) 2526 is actually a partial melt residue of an enstatite chondrite-like lithology that experienced ~20 vol% partial melting. We suggest that the heat source was internal to the parent body. The FeS-Fe,Ni and plagioclase-enstatite partial melts were removed from the parent lithology, leaving NWA 2526 as a residue highly depleted in troilite and lacking plagioclase. Sub-solidus slow cooling and annealing is responsible for the coarse-grained, recrystallized texture of the rock. We also suggest that the parent lithology of NWA 2526, prior to partial melting, experienced a shock event which formed the curvilinear trails of blebs of minor troilite and rare metal that are enclosed in enstatite crystals; thus, these represent relicts. After partial melting and annealing, NWA 2526 experienced a second, relatively mild impact event (<~20 GPa) that caused formation of the polysynthetic twinning in the enstatite.

We suggest that the meteorite Zakłodzie, which has been referred to as a "primitive enstatite achondrite" (Przylibski et al. 2005), did not form from a magma of internal origin, but that it is an impact-melt breccia of enstatite chondrite-like parentage, as previously discussed by Burbine et al. (2000) and Keil (2007).

Finally, the "metal-rich enstatite meteorite with achondritic texture" Itqiy (Patzer et al. 2001) formed by processes very similar to those responsible for formation of NWA 2526 and is also the residue of ~20 vol% partial melting of an enstatite chondrite-like parent lithology, with the FeS-Fe,Ni and plagioclase-enstatite partial melts having been removed from the residue. It also experienced an impact event after partial melting that was responsible for the formation of the mixed Mg-Mn-Fe-sulfides and the shock stage S3 features of the enstatite. These similarities indicate that NWA 2526 and Itqiy may have formed on the same parent body. This body was different from the EH, EL, Shallowater and aubrite parent bodies, and NWA 2526 and Itqiy may represent samples from yet another, fifth enstatite meteorite parent body.

INTRODUCTION

In the world's meteorite collections, there are rocks that are interpreted as the residues of partial melting of ordinary chondrite-like precursor lithologies. These are the acapulcoites-lodranites and winonaites-silicate inclusions in IAB-IIICD irons (McCoy et al. 1996, 1997a, 1997b; Benedix et al. 1998, 2000). While the parent lithologies were heated by internal heating to temperatures exceeding their solidus temperatures, thus causing partial melting and recrystallization, these rocks did not crystallize from melts, as did the differentiated achondrites (e.g., Weisberg et al. 2006) and impact-melt rocks (e.g., McCoy et al. 1995; Keil 2007). These rocks have recrystallized textures but petrologic characteristics (including occurrence of occasional relict chondrules), and whole-rock chemical and/or isotopic compositions that indicate close affinities to the primitive ordinary chondritic parent rocks from which they were derived (e.g., Prinz et al. 1983). The partial melts may have been mobilized but not removed from the parent lithology (e.g., the acapulcoites; McCoy et al. 1996), or they may have been removed to varying degrees (e.g., the lodranites; McCoy et al. 1997a, 1997b). The parent lithologies of these rocks were similar in composition, but not identical, to ordinary chondrites (e.g., Palme et al. 1981), but no meteorites of the unadulterated chondritic precursor rocks seem to exist in the world's meteorite collections (McCoy et al. 1996, 1997a, 1997b; Benedix et al. 1998, 2000).

The Northwest Africa (NWA) 2526 meteorite, a single stone originally of 42.9 grams, was purchased on June 26, 2003, from a dealer at St. Marie-aux-Mines, France, and had been recovered at an unknown locality in northwest Africa. It was originally classified as an enstatite achondrite with ~10% metal (Russell et al. 2005). However, our mineralogic, petrologic and chemical studies indicate that this highly recrystallized metal-rich rock, while achondritic in texture and consisting of major enstatite, is not an enstatite achondrite (aubrite) sensu stricto, i.e., a rock that crystallized from a melt. Rather, we suggest that it is the residue of a relatively low degree (>10–20 vol%) of partial melting and subsequent annealing not of an ordinary chondrite-like, but of an enstatite chondrite-like precursor lithology, although a direct link to known EH or EL enstatite chondrites cannot be established with certainty. We base this conclusion on the relatively high content of metallic Fe,Ni and very low content of troilite, the absence of plagioclase, and the recrystallized texture of the rock. We suggest that the parent lithology was heated to sufficiently high temperatures to cause partial melting and formation of FeS-Fe,Ni and plagioclase-enstatite partial melts, which were removed from the parent lithology, thus explaining the very low FeS and the relatively high Fe,Ni contents and the lack of plagioclase in the rock.

SAMPLES AND ANALYTICAL TECHNIQUES

Two polished thin sections (PL03170, PL06056) as well as a 6 gram specimen are located at the Institute für Planetologie, University of Münster, Germany. We studied the polished thin sections by optical microscopy in transmitted and reflected light. A JEOL 840A scanning electron microscope (SEM) was used to resolve the fine-grained interstitial material of the rock and to identify phases with a Pentafet detector (Oxford Instruments) for energy dispersive (EDS) semiquantitative elemental analysis using the INCA analytical program provided by Oxford Instruments. Quantitative mineral analyses were obtained using a JEOL 8900 electron microprobe operated at 15 keV and a probe current of 15 nA. Corrections for differential matrix effect were made using the $\Phi\rho(z)$ procedure of Armstrong (1991).

RESULTS

Texture and Mineralogy

Hand specimen inspection of the small meteorite indicates that it is relatively coarse-grained, lacks chondrules, and contains ~10 vol% of unweathered metallic Fe,Ni. Thin section microscopy confirms the coarse-grained, achondritic texture of the rock. It is dominated by equigranular grains of polysynthetically twinned enstatite (~85 vol%) which range in size from ~0.4–1.0 mm, although some as large as 2 mm were also observed (Fig. 1), and ~10–15 vol% of kamacite + terrestrial weathering products of kamacite parentage; all other phases make up <~1 vol% of the rock. The texture is distinctly recrystallized (metamorphic), with frequent 120° triple junctions between enstatite crystals, suggesting that the rock was extensively annealed. Kamacite is fresh in places and partially altered to terrestrial hydrated iron oxide weathering products in others. An XRF bulk rock analysis courtesy of Herbert Palme and Tony Schulz indicates a total of 18.5 wt% Fe and 1.07 wt% Ni. The Ni content of kamacite in NWA 2526 is ~5.7 wt% (Table 2), which suggests that the bulk kamacite content of the meteorite must have been ~18.8 wt%, roughly in agreement with the bulk Fe content of the rock determined by XRF of 18.5 wt%. Assuming a density of the metallic Fe,Ni of 7.5 g/cm^3 and a bulk density of the rock of 3.7 g/cm^3 (Keil 1962), the 18.5 wt% kamacite convert to ~9.2 vol%. In spite of the many uncertainties introduced, for example, by our assumption of closed-system weathering and by possible unrepresentative sampling of the coarse-grained rock for XRF analysis, this result is nevertheless roughly in agreement with the estimated modal kamacite content of 10–15 vol%.

Minor phases include troilite, daubreelite, schreibersite, and Si-rich melt areas (Figs. 2a–d). Feldspar, a common phase in enstatite chondrites and achondrites (aubrites) (e.g., Keil 1968; Watters and Prinz 1979), was not observed. Within the enstatite crystals occur tiny grains and blebs of opaque minerals (mostly troilite and some kamacite) that are arranged in curvilinear trails (Figs. 2c and 2d) which do not follow the cleavage planes of enstatite. We speculate that these inclusions formed by impact-generated "shock-darkening" (Rubin 1992) of the parent lithology of NWA 2526 prior to partial melting and annealing (see discussion below). Considering the bulk rock, most of the minor sulfide and schreibersite grains occur closely associated with metallic Fe,Ni and are usually embedded in terrestrial hydrated iron oxide weathering products which resulted from the weathering of the associated metallic Fe,Ni. Troilite grains are partly converted to terrestrial weathering products (Figs. 2a and 2b), whereas daubreelite appears to be terrestrially altered along distinct crystallographic directions (Fig. 2b). In some areas, very minor Si-rich melt material occurs surrounding enstatite crystals (Fig. 2c); this material appears to be very homogeneous and glassy.

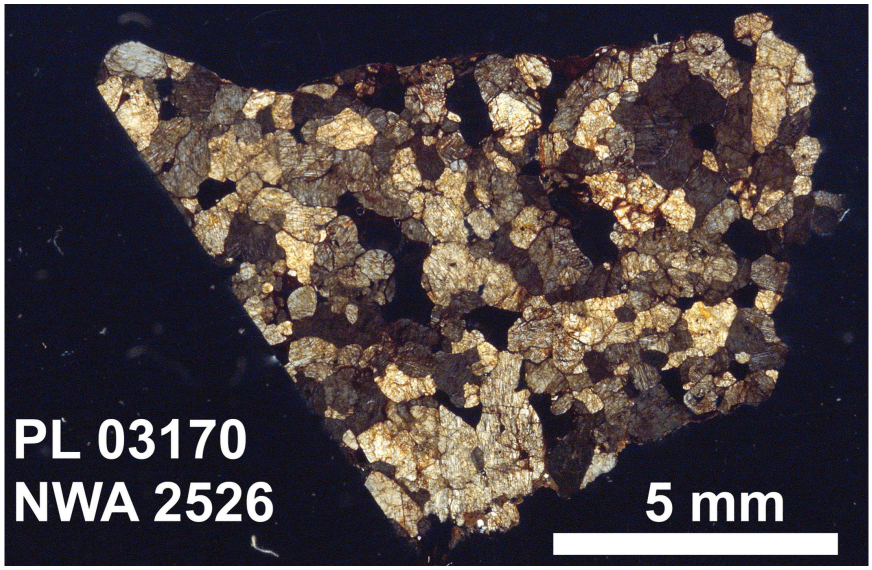

Fig. 1. Photomicrograph in transmitted light, crossed polars, of the entire polished thin section PL03170 of NWA 2526 showing the coarse-grained, equigranular, annealed texture of the rock.

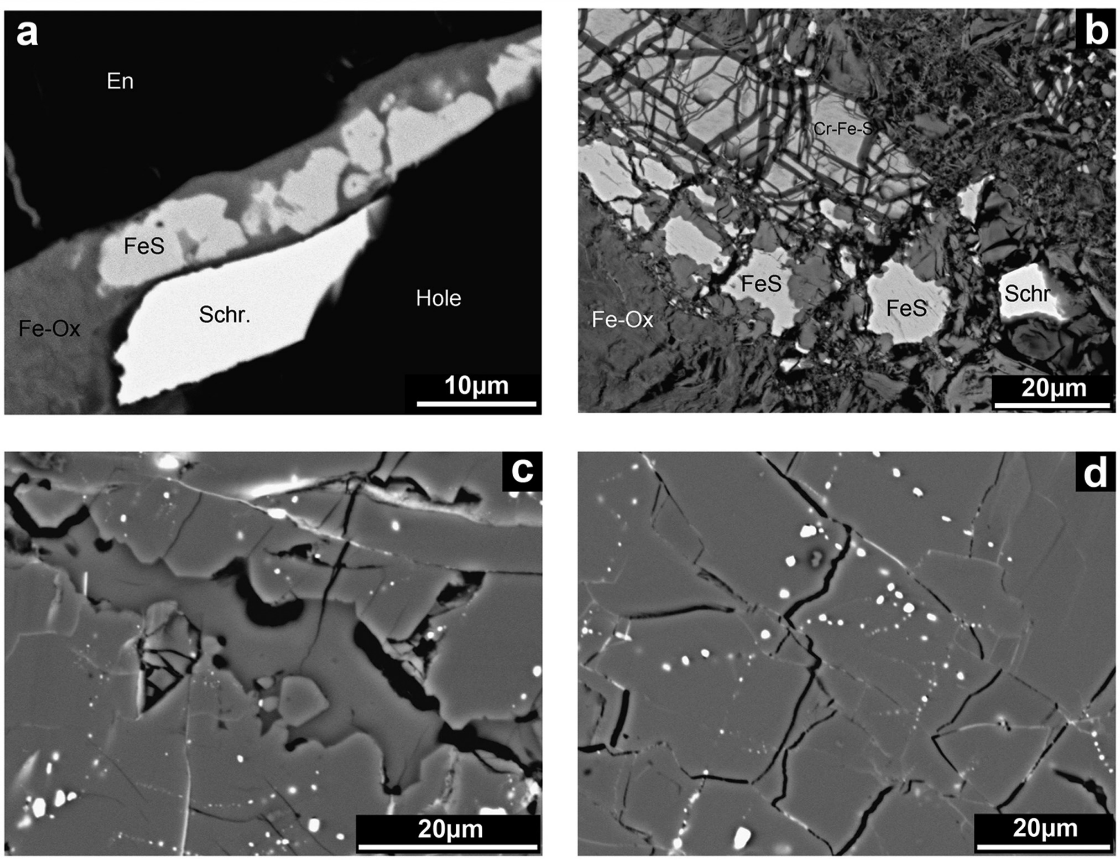

Fig. 2. Backscattered electron SEM images of various mineral assemblages in NWA 2526. a) Troilite (FeS) and schreibersite (Schr.), showing extend of terrestrial weathering into hydrated iron oxides (Fe-Ox). The mineral assemblage occurs between an enstatite crystal (En) and a hole in the section, which is an artifact of the preparation of the polished thin section. b) Troilite (FeS), daubreelite (Cr-Fe-S), and schreibersite (Schr), partially converted into terrestrial hydrated iron oxide weathering products (Fe-Ox). Note that the daubreelite appears altered along distinct crystallographic directions. c) Silica-normative melt area (center) occurring between enstatite crystals. Note that FeS and minor metallic Fe,Ni (both white) blebs within enstatite are arranged in curvilinear trails. Black areas are holes in the section. d) Troilite and minor metallic Fe,Ni blebs occur in curvilinear trails within enstatite crystals.

Table 1. Microprobe analyses of representative Si-rich melt areas (1–6) and enstatites (7–11); data in wt%; n.d. = not detected.

	1	2	3	4	5	6	7	8	9	10	11
Na_2O	1.98	2.09	1.31	1.47	2.07	2.72	0.04	n.d.	0.04	n.d.	n.d.
MgO	0.24	0.23	0.20	0.26	0.14	1.91	39.5	39.3	39.7	39.7	39.4
Al_2O_3	15.5	15.6	15.5	15.4	14.8	13.7	0.15	0.13	0.14	0.12	0.12
SiO_2	78.0	79.0	78.2	78.6	80.0	78.0	59.7	59.6	59.4	59.7	59.3
SO_3	0.90	0.93	1.10	1.07	0.83	0.99	n.d.	n.d.	n.d.	n.d.	n.d.
K_2O	0.82	0.79	0.85	0.81	0.81	1.14	0.03	<0.02	n.d.	<0.01	n.d.
CaO	0.19	0.21	0.19	0.21	0.14	0.14	0.23	0.24	0.21	0.27	0.22
TiO_2	0.04	n.d.	n.d.	<0.02	<0.02	n.d.	0.04	n.d.	n.d.	n.d.	<0.03
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	<0.01	n.d.	n.d.	n.d.	<0.01	n.d.	<0.02
MnO	n.d.	<0.02	0.03	0.04	0.08	0.04	0.03	0.03	n.d.	0.05	0.03
FeO	0.17	0.17	0.18	0.21	0.22	0.20	0.15	0.12	0.07	0.11	0.18
Total	97.84	99.02	97.56	98.07	99.09	98.84	99.87	99.42	99.56	99.95	99.25

Note: Considering the reduced nature of the meteorite, it is entirely possible that sulfur is present as S.

Table 2. Microprobe analyses of representative schreibersite (1–2) troilite (3–6), daubreelite (7–9), and metal (10–11); data in wt%; n.d. = not detected.

	1	2	3	4	5	6	7	8	9	10	11
Si	0.36	0.40	<0.01	0.04	0.03	<0.02	n.d.	<0.02	0.03	4.9	5.0
P	13.4	13.6	n.d.	<0.03	<0.02	<0.02	<0.01	<0.01	<0.01	0.11	0.04
S	0.09	0.06	37.8	36.9	37.4	37.3	44.3	43.9	44.30	n.d.	<0.02
Ca	<0.03	<0.02	0.04	0.04	<0.02	0.02	0.06	0.06	0.07	n.d.	<0.01
Ti	<0.03	n.d.	1.19	0.34	0.49	1.54	0.06	0.05	<0.01	<0.01	n.d.
Cr	0.08	0.11	1.77	0.98	0.97	1.60	35.1	36.4	37.3	n.d.	n.d.
Mn	0.20	n.d.	0.17	0.07	0.05	<0.03	0.22	0.28	0.22	n.d.	n.d.
Fe	77.1	76.3	61.4	63.5	63.6	61.2	20.6	19.9	19.3	91.2	91.5
Co	0.20	0.18	0.06	<0.03	0.15	<0.02	<0.02	0.04	<0.01	0.36	0.37
Ni	10.3	10.8	0.09	0.06	0.08	0.14	<0.02	n.d.	n.d.	5.54	5.82
Total	101.72	101.42	102.52	101.93	102.77	101.80	100.34	100.63	101.22	102.11	102.73

MINERAL CHEMISTRY

Enstatite is very uniform in composition and approaches the pure Mg-pyroxene endmember, with only ~0.1–0.3 mol% Fs and ~0.4–0.5 mol% Wo (Table 1), typical for the highly reduced enstatite meteorites (e.g., Keil 1989). The true Fs content is possibly even lower, because the tiny inclusions and blebs of troilite and kamacite in the curvilinear trails within enstatite (Figs. 2c and 2d) may have been overlapped by the beam of the electron microprobe during enstatite analysis. The very minor silica-normative melt areas which occasionally are found surrounding enstatite crystals (Fig. 2c) are high in SiO_2 (~80), Al_2O_3 (~15), Na_2O (1.3–2.7), and K_2O (~0.8–1.2), and very low in FeO (0.17–0.22) and MgO (0.14–1.9); the sulfur content of 0.83–1.1 is given as SO_3 but, considering the highly reduced nature of the assemblage, may well be present as S (all in wt%) (Table 1). The metallic Fe,Ni is characterized by remarkably high contents of Si of ~5 wt% (Table 2). By comparison, Si in kamacite increases from ~0.3–0.5 wt% in EL3 chondrites to 0.9–1.8 wt% and 1.1–1.7 wt% in EL5 and EL6 chondrites, respectively, whereas in EH3 chondrites it is ~2 wt% and increases to ~4 wt% in EH6 chondrites (Brearley and Jones 1998, based on data of Keil 1968; Sears et al. 1982, 1984; Ikeda 1989; Zhang et al. 1995). In aubrites, the Si contents of kamacite vary between 0.12–2.44 wt% (Watters and Prinz 1979). Thus, the Si content of kamacite in NWA 2526 is most similar to that of EH6 enstatite chondrites.

None of the minor minerals in NWA 2526 have characteristic compositions that hint at the specific nature of the parent lithology of the rock. Troilite, for example, has between 0.3 and 1.5% Ti and 1.0–1.8% Cr (Table 2). For comparison, troilite in type 3–6 ELs has up to 0.8% Ti and 1.5% Cr, whereas EHs have troilite with up to 0.5% Ti and 3.7% Cr (all in wt%; Keil 1968; Zhang et al. 1995; Brearley and Jones 1998). In aubrites, troilite varies considerably in Ti and Cr contents (e.g., Mittlefehldt et al. 1998). Similarly, the compositions of daubreelite and schreibersite are not diagnostic of the parent lithology. Daubreelite in NWA 2526 has Mg, Ca, Ti, and Zn contents near or below the detection limit and Mn of 0.2–0.3%, whereas daubreelite in ELs and EHs has significant Mn (0.3–2.8%) and some grains have remarkably high Zn contents (up to 8.1%) (Keil and Anderson 1965; Keil 1968; Buseck and Holdsworth 1972; Rubin 1984; El Goresy et al. 1988; Brearley and Jones 1998).

Oxygen Isotopic Composition

The oxygen isotopic compositions of NWA 2526 were kindly determined by Dr. Karen Ziegler in Professor E. D. Young's laboratory at the University of California, Los Angeles, with the following results: $\delta^{17}O = 2.8$; $\delta^{18}O = 5.2$; $\Delta^{17}O = 0.04$. These compositions are typical for aubrites and EH and EL enstatite chondrites (Clayton et al. 1984), confirming the enstatite meteorite parentage of the rock.

DISCUSSION

Origin of NWA 2526

The original description classifying NWA 2526 as some kind of an enstatite achondrite (Russell et al. 2005) was based on its coarse-grained, chondrule-free texture and its mineralogical composition of major, nearly FeO-free enstatite, ~10 vol% of Si-bearing kamacite, and minor amounts of Ti-bearing troilite, and some daubreelite, all characteristic of enstatite meteorites (e.g., Keil 1968, 1989). However, this description did not address the origin of the rock, i.e., whether it is indeed an enstatite achondrite (i.e., aubrite) sensu stricto that formed from a melt, or some kind of an anomalous impact-melt rock, or formed by an altogether different process. It is the purpose of this paper to address the origin of the rock.

We argue that NWA 2526 is not an enstatite achondrite (aubrite) sensu stricto, because such rocks do not contain high amounts of high-density phases such as kamacite. These phases would have settled out of the magma at the high temperatures and high degrees of partial melting required for the melting of enstatite chondrite-like precursor lithologies (McCoy et al. 1999). In fact, except for the aubrite Shallowater, whose origin seems to be unrelated to that of normal aubrites (Keil et al. 1989), aubrites contain between traces and 0.1 vol% kamacite (Watters and Prinz 1979). On the other hand, we estimate that NWA 2526, prior to terrestrial weathering, contained ~10–15 vol% kamacite and, considering the uncertainties in the metallic Fe,Ni content due to terrestrial weathering of the rock, these contents are approximately on par with those of typical enstatite chondrites (e.g., Keil 1968).

Furthermore, while impact-melt rocks and impact-melt breccias are common amongst enstatite chondrites (e.g., Bischoff et al. 1992, 2006; McCoy et al. 1995; Rubin 1997; Rubin and Scott 1997; Rubin et al. 1997; Leroux et al. 1997; Lin and Kimura 1998; Keil 2007), the coarse-grained, highly recrystallized and unbrecciated texture of NWA 2526 is unlike that of typical impact-melt rocks or impact-melt breccias of enstatite chondrite parentage. Unbrecciated, total impact-melt rocks of enstatite chondrite parentage such as Ilafegh 009 (Bischoff et al. 1992; McCoy et al. 1995; Leroux et al. 1997), for example, consist of large, interlocking, hypidiomorphic to euhedral laths of enstatite, often surrounded by metallic Fe,Ni. Since Ilafegh 009 crystallized from a total, relatively quickly cooled (at high temperatures) melt, it has retained minerals in abundances essentially like the inferred EL enstatite chondrite parent lithology. Specifically, it has 27.2 wt% kamacite (and schreibersite), 8.1 wt% troilite (and daubreelite), and 7.1 wt% plagioclase, quite unlike NWA 2526 which we propose has lost from its enstatite chondrite-like parent lithology much of its troilite as FeS-FeNi and plagioclase as plagioclase-enstatite partial melts during ~20% partial melting.

We suggest instead that the heat source for partial melting of NWA 2526 was not impact but was internally derived. We conclude that the rock is the residue of a relatively low degree of partial melting of an enstatite chondrite-like precursor lithology, where the partial melts were largely removed. We suggest that, upon partial melting, the first liquid, the FeS-Fe,Ni eutectic partial melt, formed at about 1000 °C and consisted of ~85 wt% troilite and 15 wt% Fe,Ni metal (e.g., Kullerud 1963; McCoy et al. 1999). If the precursor rock of NWA 2526 was indeed enstatite chondrite-like, then it contained ~6.6 wt% (or ~8.1 vol%) troilite (Keil 1968). Since nearly all of the troilite was removed from the rock as a eutectic melt, that would amount to ~9 vol% of partial melt. At slightly higher temperatures, around 1100 °C, plagioclase-enstatite partial melting occurred (McCoy et al. 1999), and since enstatite chondrites typically contain ~8 vol% plagioclase (Mason 1966) and NWA 2526 does not contain this mineral, ~10 vol% of a plagioclase-pyroxene partial melt must have been removed. Thus, the total partial melting can very roughly be estimated to have been between 15–20 vol%. Once 10–20 vol% of partial melting has taken place, modeling suggests that melt migration should be extremely efficient (McCoy et al. 1997b). Thus, upon removal of these partial melts, the residue would be highly depleted in troilite but still contain a high proportion of its original metallic Fe,Ni content, and would lack plagioclase, as is the case for NWA 2526. In support of the partial melt hypothesis, we also note that the very minor silica-rich melt material with minor MgO and S contents (Table 1) surrounding enstatite crystals in NWA 2526 (Fig. 2c) is remarkably similar in composition to "a very small quantity of silicate partial melt rich in SiO_2 and with minor MgO and S" formed at 1100 °C in partial melting experiments of the Indarch (EH4) enstatite chondrite (McCoy et al. 1999).

Thus, we suggest that NWA 2526 formed in processes similar to those that formed the lodranites (McCoy et al. 1997a, 1997b), i.e., by partial melting of 10–20 vol% due to internal heating, removal of the FeS-Fe,Ni and pyroxene-plagioclase partial melts, followed by subsolidus annealing. This accounts for the remarkable textural similarities between the lodranites and NWA 2526, i.e., the lack of chondrules and the coarse-grained, highly recrystallized texture. Since the parent lithologies of the lodranites were akin to ordinary chondrites and of NWA 2526 akin to enstatite chondrites, the mineralogy and mineral compositions of the two types of rocks are, of course, different.

As is the case with the acapulcoites and lodranites, the precise parent lithology for NWA 2526 cannot be identified with certainty, and no unadulterated rock of that lithology appears to exist in the world's meteorite collections. However, the mineralogical and oxygen isotopic compositions of NWA 2526 are consistent with the suggestion that its parent lithology was enstatite chondrite-like, i.e., was highly reduced and contained abundant Si-bearing kamacite of ~10–15 vol% as well as Ti-bearing troilite, schreibersite, and daubreelite, all characteristic of enstatite chondrites (e.g., Keil 1968, 1989). The very high Si content of kamacite of ~5 vol% mentioned above is a factor of >2 higher than in aubrites and EL3-6 and EH3 enstatite chondrites, but is similar to the Si contents of EH6 enstatite chondrites of ~4 vol%. This hints that the parent lithology of NWA 2526 may have been similar to EH6 material, although there are too many uncertainties to have much confidence in this suggestion.

The curvilinear trails of tiny blebs of minor troilite and some metallic Fe,Ni within enstatite crystals (Figs. 2c and 2d) of NWA 2526 are very similar to those which Rubin (1992) described in detail from silicates in CK and ordinary chondrites. He attributes the origin of these "shock-darkened" silicates to shock prior to annealing of the chondrites. Similarly, we speculate that these curvilinear trails in NWA 2526, which do not follow the currently visible cleavage plains of enstatite, formed by shock mobilization of FeS and Fe,Ni and trapping in fractures and earlier cleavage planes of neighboring enstatite crystals of the enstatite chondrite-like parent lithology of NWA 2526 prior to partial melting, annealing and crystal growth. The bleb-bearing enstatite crystals did not melt during the partial melting episode experienced by the parent lithology of NWA 2526, and they are thus relicts. Finally, NWA 2526 experienced a second, relatively mild shock event after partial melting and annealing which is responsible for the polysynthetic twinning exhibited by the enstatite crystals (note that the curvilinear trails do not follow the polysynthetic twinning). We suggest that this was a relatively mild shock event, as mechanical twinning can form well below ~10 GPa (e.g., Hornemann and Müller 1971; Hörz and Quaide 1973; Stöffler et al. 1988; Bischoff and Stöffler 1992). That this event was relatively mild is also indicated by the fact that the coarse metal-bearing assemblages in the matrix of the rock show no shock-induced raggedness and no small troilite grains within larger metal grains, which is typical for highly shocked chondrites (e.g., Stöffler et al. 1991).

Comparison of NWA 2526 to Other Unusual Enstatite Meteorites

The Zakłodzie enstatite meteorite has been called a "primitive enstatite achondrite," but one that is interpreted to have formed on its parent body from a magma of internal origin (Przylibski et al. 2005). These authors did not propose that Zakłodzie formed by partial melting of an enstatite chondrite precursor lithology and, in a follow-up paper state that the meteorite "is not an enstatite chondrite" (Karwowski et al. 2007). However, Keil (2007) suggested that their data and textural observations suggest that the rock is a quickly cooled impact-melt breccia of enstatite chondrite parentage, as had previously been suggested by Burbine et al. (2000). Specifically, Keil (2007) noted that the relict chondrule shown in Fig. 2 in Przylibski et al. (2005) and identified as such by these authors is a common feature of impact-melt breccias of enstatite chondrite parentage (e.g., Rubin and Scott 1997). Keil (2007) also noted that the euhedral enstatite laths surrounded by metallic Fe,Ni are typical for enstatite chondrite impact-melt rocks and breccias and are indicators of impact melting followed by relatively fast cooling (e.g., Rubin and Scott 1997). Furthermore, the rock contains ~20 wt% of high-density opaque phases which would be expected to have settled out of the magma by density separation in a slowly formed and slowly cooled total melt ("magma") of internal origin, whereas these phases can be retained in quickly heated and quickly cooled impact melts. Finally, Keil (2007) has shown that keilite [$(Fe_{>0.5},Mg_{<0.5})S$], a mineral occurring in Zakłodzie (Karwowski et al. 2007), according to the phase relations and experimentally determined stability parameters and required cooling rates established by Skinner and Luce (1971) for the system MgS-MnS-CaS-FeS, is only stable in quickly cooled impact-melt rocks and impact-melt breccias.

However, Patzer et al. (2001) described the Itqiy metal-rich enstatite meteorite which, in many of its mineralogical and textural properties, is similar to NWA 2526. It consists of some 75 vol% subhedral, equigranular, millimeter-sized enstatite of $Fs_{0.2}$, 25 vol% of millimeter-sized kamacite, only a few tiny intergrowths of sulfides and kamacite, and completely lacks plagioclase. Patzer et al. (2001) correctly pointed out that the rock must have experienced two thermal events. During the first high-temperature heating event, partial melting produced FeS-Fe,Ni and plagioclase-enstatite melts that were removed from the rock, thus accounting for the near absence of sulfides, the lack of plagioclase, the homogeneous silicate compositions including rare earth abundances and, during annealing, the highly recrystallized, coarse-grained texture. The heating, partial melting and annealing events were followed by a shock event that melted the remaining very minor sulfides and caused formation of the rare, mixed Mg,Mn,Fe-sulfides of highly variable compositions and the shock stage S3 features of the enstatite (Rubin et al. 1997). While Patzer et al. (2001) point out the affinity of this rock to enstatite chondrites, they correctly conclude that, on the basis of the available mineralogical and chemical data, reliable kinship of the rock to either EH or EL enstatite chondrites cannot be established.

We agree with the conclusions of Patzer et al. (2001) and would describe Itqiy as a partial melt residue of enstatite chondrite parentage. We suggest that Itqiy resulted from ~20 vol% partial melting of an enstatite chondrite-like parent lithology that experienced loss of FeS-Fe,Ni and plagioclase-enstatite by removal from the residue. While the precise parentage to EH or EL enstatite chondrites cannot be established, the parent lithology was clearly enstatite-chondrite-like. Thus, Itqiy formed by processes very similar to those that are responsible for the formation of NWA 2526 and, in fact, the two rocks may have formed on the same parent body. We are unable to establish an unambiguous mineralogical or chemical kinship of NWA 2526 and Itqiy to any of the four known enstatite meteorite parent bodies (the EH, EL, Shallowater and aubrite parent bodies [Keil 1968, 1989; Sears et al. 1982; Okada et al. 1988; Keil et al. 1989]). We therefore speculate that it is possible that NWA 2526 and Itqiy actually represent samples from yet another, fifth enstatite meteorite parent body.

CONCLUSIONS

We conclude that NWA 2526 is the residue of ~20 vol% of partial melting of a parent lithology of enstatite chondrite-like material. Prior to partial melting, the parent lithology suffered an impact event that caused mobilization of small amounts of troilite and some metallic Fe,Ni and dispersion through fractures into neighboring enstatite crystals, forming the curvilinear trails of tiny blebs of minor troilite and traces of metallic Fe,Ni. These trails were protected within enstatite, and thus neither the host enstatites nor the sulfide-metal trails did partially melt; they thus are relicts. During progressive heating and partial melting, the interstitial FeS-Fe,Ni formed a eutectic partial melt consisting of ~85 vol% FeS and 15 vol% Fe,Ni, at approximately 1000 °C and at somewhat higher temperatures (~1100 °C) a plagioclase-enstatite partial melt. These partial melts were removed from the parent lithology, thus leaving a residue in the form of NWA 2526, with only very minor troilite but major Fe,Ni contents and lack of plagioclase. We suggest that the heat source for partial melting was internally generated and that the rock resembles, in its mode of origin, the lodranites, except that their parent lithology was ordinary chondrite-like. A mild shock event (<~10 GPa) after partial melting and annealing is responsible for the formation of the polysynthetic twinning of the enstatite. We agree with Burbine et al. (2006) and Keil (2007) that the enstatite meteorite Zakłodzie did not form by internal heating but is an impact-melt breccia of enstatite chondrite-like parentage. We also conclude that the meteorite Itqiy formed by processes similar to those that formed NWA 2526 and is also a partial melt residue of ~20 vol% partial melting of an enstatite chondrite-like parent lithology. These similarities suggest that NWA 2526 and Itqiy may have formed on the same parent body. This body was different from the EH, EL, Shallowater and aubrite parent bodies (Keil 1989), and NWA 2526 and Itqiy actually may represent samples from yet another, fifth enstatite meteorite parent body.

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