QUE 94204: A PRIMITIVE ENSTATITE ACHONDRITE PRODUCED BY PARTIAL MELTING OF AN E-CHONDRITE-LIKE PROTOLITH

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Introduction: QUE 94204, an enstatite achondrite, is a coarse-grained, highly recrystallized, chondrule-free and unbrecciated rock dominated by equigranular crystals of polysynthetically-twinned orthoenstatite of nearly end-member composition ($En_{98.4(1)}Wo_{0.4(1)}Fs_{0.2(1)}$), with interstitial plagioclase, kamacite and troilite. Petrographic evidence in the form of ~120º triple junctions and immiscible textures between metal and sulfides indicates that QUE 94204 has undergone limited partial melting. Kamacite in QUE 94204 contains ~2.26-2.52 wt. % Si, similar to metamorphosed EH chondrites [3]. Plagioclase, by contrast, has between 4.31 and 7.04 CaO and between 0.25 and 0.38 K_2O, closer in composition to plagioclase from metamorphosed EL chondrites [3]. QUE 94204 troilite contains up to 3.24 wt. % Ti and less than 0.01 wt. % Cr, consistent with extensive thermal metamorphism of an E-chondrite-like precursor [3,4]. Results presented in this study indicate that QUE 94204 is the result of a low degree (~5-20 vol. %) partial melting of an E-chondrite-like protolith. Textural and chemical evidence suggests that during the metamorphism of QUE 94204, melts formed first at the Fe,Ni-FeS cotectic near ~900 ºC, followed by plagioclase ± pyroxene silicate partial melts near ~1100 ºC. Neither the Fe,Ni-FeS nor the plagioclase ± pyroxene melts were efficiently segregated or extracted. QUE 94204 belongs to a grouplet of similar 'primitive enstatite achondrites' that are analogous to the acapulcoites-lodranites, but that have resulted from the partial melting of enstatite chondrites rather than ordinary chondrites.

Materials and methods: A polished thin section (NASA ANSMET section QUE94204-26) was examined in transmitted and reflected light (Fig. 1). Mineral abundances were estimated by point counting. Mineral compositions were determined using a JEOL8900R electron microprobe with a 1 μm focused beam, 15 kV accelerating voltage and 30 nA beam current. Separate calibrations for silicate, metal, and sulfides were performed using natural and synthetic mineral standards. A ZAF correction was applied to all EPMA data [1]. Micro X-ray Diffraction (μXRD) data were collected for selected areas using a Bruker-AXS D8 Discover diffractometer with Cu Kα radiation (λ = 1.5418 Å) produced by a sealed tube source operating at 40 kV accelerating voltage and 40 mA beam current and a nominal beam diameter of 500 μm [2].

Petrography: QUE 94204 is a coarse-grained, unbrecciated, achondritic rock dominated by equigranular grains of polysynthetically twinned enstatite, with common ~120° triple junctions. QUE 94204 bears a striking resemblance to NWA 2526, which has been interpreted by Keil and Bischoff [3] to be a partial melt residue of an E-chondrite-like protolith. Unlike NWA 2526, however, QUE 94204 contains both plagioclase and troilite. The remainder of the meteorite consists of Si-bearing kamacite; cristobalite; and terrestrial weathering products including goethite with gypsum and calcite.

The thin section is dominated by coarse grained equigranular, rounded enstatite crystals that comprise ~70 vol. % of the section. Enstatite crystals contain abundant curviplanar trails of troilite and/or metal inclusions. Irregular fractures pervade the enstatite crystals. Plagioclase is interstitial to enstatite grains, and also contains curviplanar trails of troilite-metal inclusions that occasionally continue between enstatite and plagioclase. Plagioclase comprises ~8 vol. % of the section. All plagioclase grains observed exhibit albite twining and lack compositional zoning as demonstrated optically and by Electron Probe Micro Analysis (EPMA). Cristobalite, as confirmed by μXRD, is a minor constituent of QUE 94204, comprising ~1-3 vol. % of the section, and it is commonly associated with the edges of enstatite crystals. Staining of the silicate phases by Fe-oxyhydroxide terrestrial weathering products is pervasive throughout the section. Kamacite comprises ~5 vol. % of the section. Metal and sulfides occur interstitially and as rounded blebs enclosed in silicates. Where sulfides and metal occur in contact, they display immiscible textures. Troilite is by far the most common sulfide observed, comprising ~5 vol. % of the section. Daubreelite is rare, and is always associated with troilite, commonly as exsolution lamellae. Metal and sulfides are commonly substantially weathered and replaced, partially or completely, by an assemblage of fine-grained secondary minerals including goethite, gypsum and calcite. Terrestrial weathering products also form veins along some grain boundaries, it is not possible to be certain whether these veins correspond to pre-terrestrial structures or are entirely the result of the migration of terrestrial weathering products in solution. Terrestrial weathering products comprise ~9 vol. % of the section.

Inclusions in QUE 94204 silicates: Two major types of inclusions have been observed in QUE 94204 silicates. The first inclusion type consists of curviplanar trails of micron to submicron troilite and/or

kamacite inclusions that may continue across enstatite and plagioclase grain boundaries, and do not appear to follow twin or cleavage planes. The troilite and/or kamacite inclusions appear to follow annealed fractures that originally cross-cut silicate grain boundaries and may be the result of thermal annealing of shock-injected Fe,Ni-FeS melts. The second type of inclusion consists of euhedral, acicular to lath-like transparent inclusions in enstatite, up to several tens of microns in their longest dimension with crystallographically-controlled forms.

Mineral chemistry: QUE 94204 orthopyroxene is very uniform in composition with between 0.04 and 0.75 wt. % FeO and 0.20 to 0.41 wt. % CaO. The composition of enstatite is probably even more Fe-poor than noted, as it is likely impossible that none of the Fe-rich troilite-metal inclusions and Fe-oxyhydroxide-dominated terrestrial weathering products were included in the EPMA excitation volumes. Plagioclase composition displays moderate variability, ranging from 4.31 to 7.04 wt. % CaO and from 0.28 to 0.38 wt. % K_2O ($Ab_{66.1(1)-78.3(1)}An_{20.6(1)-34.1(1)}Or_{1.6(1)-2.2(1)}$). Kamacite composition is very uniform, with 5.44 to 6.69 wt. % Ni and 2.27 to 2.52 wt. % Si. Troilite contains between 1.20 and 3.24 wt. % Ti. Cristobalite-bearing regions (commonly observed at the interface of enstatite and metal) also contain Al_2O_3, K_2O, and Na_2O.

Micro X-ray diffraction (μXRD): Micro XRD confirmed the major mineral identifications made using optical petrography and EPMA. Micro XRD also identified the fine-grained weathering products goethite, gypsum and calcite; and confirmed the presence of cristobalite.

Discussion and Conclusions: QUE 94204 is an enstatite meteorite which is the product of a low degree of partial melting of an enstatite chondrite-like precursor material. Both cotectic Fe,Ni-FeS and plagioclase ± pyroxene partial melts were formed on the QUE 94204 parent asteroid, but temperatures did not exceed the solidus of enstatite (except perhaps in very localized regions). The presence of both immiscible Fe,Ni-FeS and plagioclase ± pyroxene partial melts in close spatial association within the interstices of enstatite grains suggests that melt extraction and migration were inefficient processes on the QUE 94204 parent asteroid. The petrogenesis of QUE 94204 was analogous to that of the acapulcoite and lodranites, but with an E-chondrite like precursor lithology. Endogenous and exogenous heat sources could both have contributed to the thermal metamorphism and partial melting of the QUE 94204 protolith. Our data cannot rule out either endogenous or exogenous heating, and might best be explained by contributions from both.

QUE 94204 is similar in mineralogy, mineral chemistry and texture to Northwest Africa 2526, another enstatite chondrite partial melt [3], but differs in that it contains some plagioclase, troilite and other sulfides. QUE 94204 and its paired samples QUE 97289 and QUE 97348, along with NWA 2526, Itqiy, and possibly Yamato 82189 belong to a small, but potentially important grouplet of 'primitive enstatite achondrites', analogous to acapulcoites and lodranites. It is not possible to unambiguously determine whether any material presently known from the world's meteorite collection corresponds to the protolith of QUE 94204. As suggested for NWA 2526 and Itqiy by [3], this grouplet of meteorites may sample a fifth enstatite meteorite parent asteroid.

References: [1] J. T. Armstrong, *Microbeam Analysis* 4, 177 (1995). [2] R. L. Flemming, *Canadian Journal of Earth Sciences* 44, 1333 (2007). [3] K. Keil, A. Bischoff, *MAPS* 43, 1233 (2008), [4] A. Patzer et al., *MAPS* 36, 1495-1505 (2001).

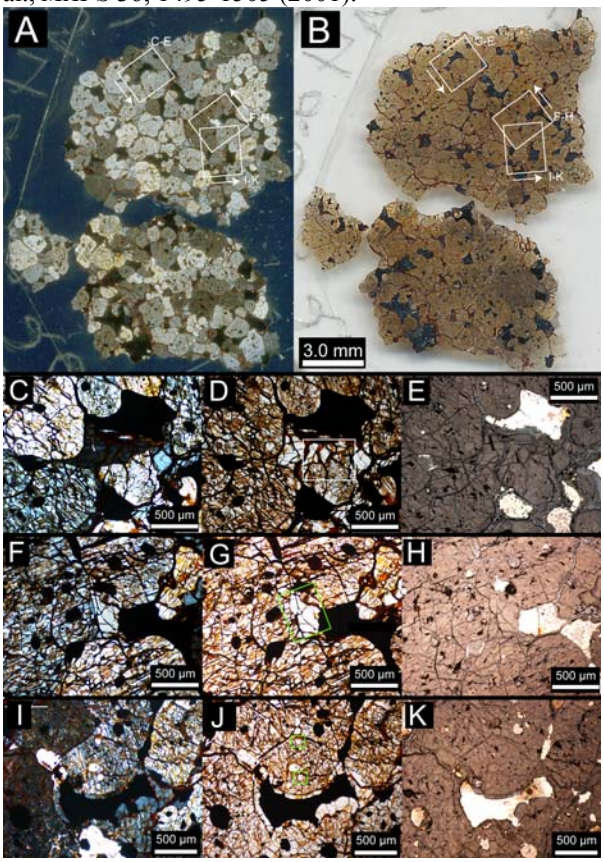

Figure 1: QUE 94204 – 26 thin section, transmitted cross-polarized (A, C, F, I); plane-polarized (B, D, G, J) and reflected (E, H, K) light. The section is dominated by equigranular, rounded, polysynthetically-twinned orthoenstatite crystals with common triple junctions and interstitial kamacite, sulfides and polysynthetically twinned plagioclase. Kamacite and troilite have been extensively replaced by terrestrial weathering products. Textural features are highly suggestive of partial melting.