1. Introduction

Northwest Africa (NWA) 10416, weighing 964 g was found in Mali, 2015. It is an olivine-phryic shergottite with a high degree of alteration present within it, unusual for shergottites. The olivine megacrysts show amber-brown altered cores and clear unaltered rims (Fig. 1), distinctive concentric colourations not previously reported in the olivine-phryic shergottites. The groundmass plagioclase and maskelynite have also been extensively altered to a secondary phase. Here we report on the petrology and alteration history of the olivine-phryic shergottite, NWA 10416, paying particular attention to the origin of the aqueous alteration seen within the meteorite.

2. Mineralogy

Mineral Liberation Analysis (MLA) reveals mineral modal abundances as: ~8 vol.% olivine megacrysts (of which ~75 vol.% has altered), ~4 vol.% groundmass olivine, ~65 vol.% clinopyroxene, ~20 vol.% plagioclase feldspar (of which ~40 vol.% has been altered), ~2.0 vol.% maskelynite (of which some has been altered) and ~2.0 vol. % minor minerals.

3. Olivine Alteration

The 1 mm megacrysts consist of amber-coloured cores surrounded by dark brown mantle zones which in turn are rimmed by clear olivine (Fig. 1). EPMA-WDS reveals that the coloured zones have not preserved their stoichiometric compositions post alteration, whereas the clear rims have, averaging Fa$_{0.5}$Fo$_{95}$. Relict igneous zonation is apparent, from Mg-rich cores to more Fe-rich rims. The amber cores contain 2.2 wt.% H$_2$O whereas the brown zones contain more than double, 5.4 wt.%. Incipient replacement features (Fig. 2) are visible in backscatter, only present in the coloured zones, they have compositions enriched in FeO and depleted in MgO. Fe-K XAS conducted at Diamond Light Source reveals the ferric content of the three distinctive zones within the megacrysts. Clear rim (Fe$_{58}$/Fe$_{22}$ = 0.03), brown mantle zone (~0.77) and amber core (~0.24).

TEM analysis (Fig. 3) reveals the altered nature of the olivine; numerous subparallel bands and some longer cross-cutting bands, interspersed throughout relict olivine. Features have a brighter contrast when viewed in bright field, indicating a lower mass density, and varying degrees of amorphization. Several void spaces are present throughout the section.

4. Plagioclase and Maskelynite Alteration

Plagioclase is of labradorite composition with minor bytownite, Ab$_{32}$An$_{45}$Or$_{23}$, and ~10 vol.% has been shock converted to maskelynite [1,2]. A large proportion, ~40 vol.%, of labradorite has been replaced by a secondary phase. EPMA-WDS measurements, when recalculated on the basis of 18 O, OH, strongly resembles a dehydrated kaolinite with an enriched CaO content. TEM analysis revealed the amorphous nature of the phase.

5.Alteration Origin: Martian or Terrestrial?

Maskelynite, the result of shock converted plagioclase and the event that lofted the rock off Mars, is observed partially replaced by kaolinite (also noted by [2,3]). Thus indicating the alteration occurred post maskelynite formation and most likely on Earth.

TEM analysis of shock-melt olivine was conducted to test if any features characteristic of aqueous alteration are present overprinting shock features (which will have formed within the shock event that lofted the rock off Mars). If true, then the alteration post-dates the shock event and is terrestrial in origin. Several 9.5 Å d-spacing’s were found interspersed throughout the grain, most likely indicating a collapsed smectite, probably saponite [4,5]. The d-spacing’s are undisturbed by any shock-features, thus the product of terrestrial alteration.

Oxygen isotopic analyses between bulk material and altered amber olivine. Our results show that the altered amber material bears a terrestrial component (δ$^{18}$O = 0.271 ‰) compared to the bulk material (δ$^{18}$O = 0.309 ‰) which essentially plots on the martian fractionation line (δ$^{18}$O = 0.271 ‰).

6. Discussion

Previous studies [1-2] have suggested that the olivine alteration is pre-terrestrial, and that the phase responsible for the olivine alteration is a Mg-bearing lauhlinite, a hydrothermal oxidation product of olivine. Although our TEM analysis shows features similar to those found in lauhlinite [6], the presence of metal oxides and/or metal nanoparticles, predicted by [7] and solely cation site vacancies, predicted by [8] was not observed.

Many factors affect silicate dissolution; composition, temp etc., [9] showed that Mg-olivine is more susceptible to alteration than its Fe counterpart under oxidizing conditions, when exposed to low T fluids. [10] detailed how An-content of plagioclase plays a large role in the dissolution rate in acidic condition, which can explain the large extent of plagioclase alteration.

Our possible model for the alteration of NWA 10416 describes how shock effects during the lofting from Mars caused veins and fracturing of the juvenile zones and maskelynite alteration. Then, during its time in NW Africa, low temperature, acidic fluids exploited the fractures and altered the olivine in a way that was controlled by the pre-existing, igneous compositional zonation. Accounting for the preference of Fo-olivine alteration and the extent of alteration across the meteorite.