# Alteration Mineral Assemblages in the NWA 10416 Olivine Phyric Shergottite

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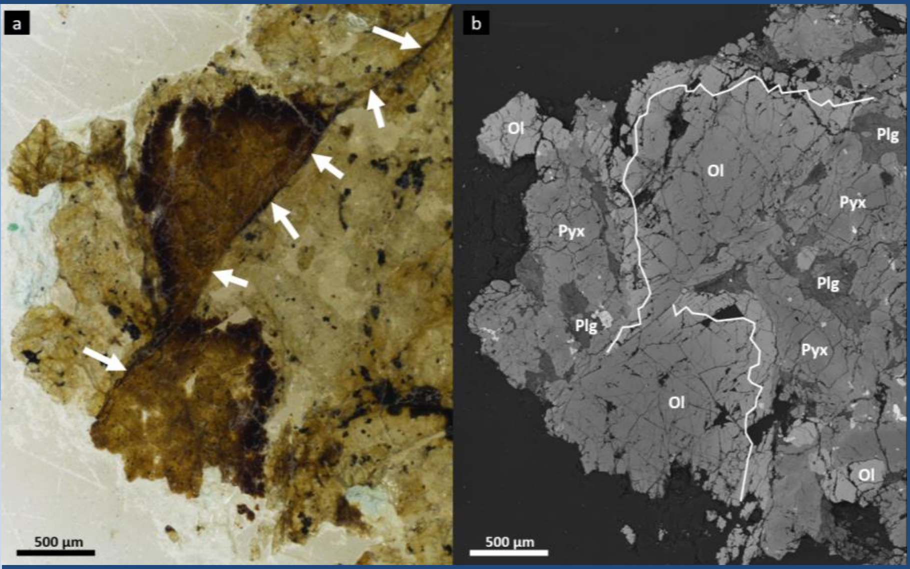
## 1. Introduction

**Northwest Africa (NWA) 10416**, weighing 964 g was found in Mali, 2015. It is an **olivine-phyric 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-phyric 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-phyric shergottite, NWA 10416, paying particular attention to **the origin of the aqueous alteration** seen within the meteorite.




▲ ***Figure 1*** – Polarised light (a) and Back Scatter Electron (BSE) (b) image comparison of a fractured olivine megacryst in NWA 10416, a shock-melt vein is present between the two halves (arrowed). Brown mantle - clear rim boundary shown as white line on BSE image. Minerals labelled: olivine (ol), pyroxene (Pyx) and plagioclase (Plg).

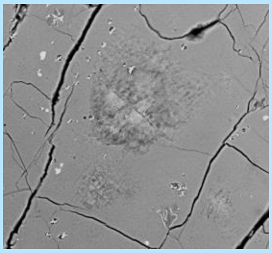
## 2. Mineralogy

**Mineral Liberation Analysis (MLA)** reveals mineral modal abundances as: **~8 vol.% olivine megacrysts** (of which ~75 vol% has been 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.**

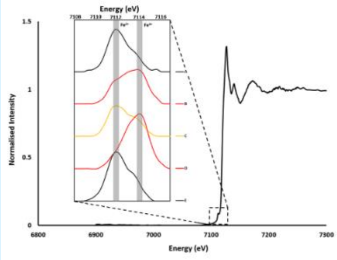
## 3. Olivine Alteration

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 there stoichiometric compositions** post alteration, whereas the clear rims have, averaging $Fo_{52}Fa_{48}$. Relict igneous zonation is apparent, from Mg-rich cores to more Fe-rich rims. The **amber cores** contains **2.2 wt.% $H_2O$** 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 ($Fe^{3+}/\Sigma Fe$ = 0.03), brown mantle zone (= 0.77)** and **amber core (= 0.24).**

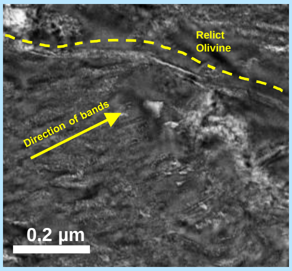
**TEM analysis (Fig. 3)** reveals the altered nature of the olivine; numerous **subparallel bands** and some **longer cross-cutting bands,** interspersed throughout **relict olivine**. Features have a brighter contrast when viewed in bright field, indicating a **lower mass density,** and varying degrees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



▲ ***Figure 2*** – Incipient replacement features present in the brown and amber zones.




▲ ***Figure 3*** – XAS spectra, with a focus on the pre-edge features, of the three coloured zones in the megacrysts.




▲ ***Figure 4*** – *HRTEM bright field image (x25k) of* alteration features seen within brown altered olivine.

## 4. Plagioclase and Maskelynite Alteration

Plagioclase is of **labradorite** composition with **minor bytownite**, $Ab_{28-44}An_{55-72}Or_{0-1}$, and **~10 vol.%** has been shock converted to **maskelynite [1,2,3].** 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 ($\Delta^{17}O$ = 0.271 ‰)** compared to the **bulk material (= 0.309 ‰)** which essentially plots on the **martian fractionation line (= 0.307 ‰).**

## 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 laihunite, a hydrothermal oxidation product of olivine**. Although our **TEM analysis** shows features similar to those found in laihunite **[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 **igneously zoned olivines**. 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.

**References: [1]** Vaci, Z. (2017). *MSc*, University of New Mexico. **[2]** Herd C. D. K. et al. (2016) *LPSC XLVII, #2527.* **[3]** Walton, E. L. (2016) *LPSC XLVII,* #1639. **[4]** Deer, W. A. (2013). An introduction to the rock forming minerals. *The Min. Soc.* **[5]** Hicks, L. J. (2014) *GCA*. **136**, 194-210. **[6]** Noguchi, T. (2009). *JGR*. **114**, E10004. **[7]** Kondoh, S. (1985). *Am. Min. Soc.* **70**, 737-746. **[8]** Xu, H. (2014). *Am. Min. Soc*. **99**, 881-889. **[9]** Hausrath E. M. and Brantley S. L. (2010) *JGR*. **115**, 2156–2202. **[10]** Gudbrandsson, S. (2014). *GCA*. **139,** 154-172.