**Formation of phosphorus-rich olivine in Dar al Gani 978 carbonaceous chondrite through fluid-assisted metamorphism**

YANG LI¹, AI-CHENG ZHANG¹,².*, JIA-NI CHEN¹, LI-XIN GU³, and RU-CHENG WANG¹

¹State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210046, China  
²Lunar and Planetary Science Institute, Nanjing University, Nanjing 210046, China  
³Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

**ABSTRACT**

Phosphorus-rich olivine (P₂O₅ > 1 wt%) is a mineral that has been reported only in a few terrestrial and extraterrestrial occurrences. Previous investigations suggest that P-rich olivine mainly forms through rapid crystallization from high-temperature P-rich melts. Here, we report a new occurrence of P-rich olivine in an ungrouped carbonaceous chondrite Dar al Gani (DaG) 978. The P-rich olivine in DaG 978 occurs as lath-shaped grains surrounding low-Ca pyroxene and olivine grains. The lath-shaped olivine shows a large variation in P₂O₅ (0–5.5 wt%). The P-rich olivine grains occur in a chondrule fragment and is closely associated with chlorapatite, merrillite, FeNi metal, and troilite. Tiny Cr-rich hercynite is present as inclusions within the P-rich olivine. The lath-shaped texture and the association with Cr-rich hercynite indicates that the P-rich olivine in DaG 978 formed by replacing low-Ca pyroxene precursor by a P-rich fluid during a thermal event, rather than by crystallization from a high-temperature melt. The large variation of P₂O₅ within olivine grains on micrometer-scale indicates a disequilibrium formation process of the P-rich olivine. The occurrence of P-rich olivine in DaG 978 reveals a new formation mechanism of P-rich olivine.

**Keywords:** Phosphorus-rich olivine, fluid-assisted metamorphism, Dar al Gani 978, carbonaceous chondrite

**INTRODUCTION**

Olivine is a common mineral in terrestrial igneous rocks and extraterrestrial materials. Most natural olivine grains contain very low concentrations of P₂O₅ due to a low partition coefficient for P between olivine and melt (<0.1, Anderson and Greenland 1969; Brunet and Chazot 2001; Milman-Barris et al. 2008; Boesenberg and Hewins 2010). Despite its extreme rarity in nature, several occurrences of P-rich olivine (P₂O₅ > 1 wt%) have been reported in a few terrestrial and extraterrestrial samples, with various geological settings. In terrestrial samples, P-rich olivine has been reported in three different settings (Goodrich 1984; Agrell et al. 1998; Tropper et al. 2004; Schneider et al. 2013). First, Goodrich (1984) described dendritic P-rich olivine (0.2–2.7 wt% P₂O₅) within silicate inclusions in an iron-carbon alloy from Disko land, West Greenland. It was suggested that this P-rich olivine is a result of rapid crystallization from supersaturated liquids under the chemical condition of high-P₂O₅ contents coupled with low-SiO₂ contents, low fO₂ (Goodrich 1984). Second, Agrell et al. (1998) reported P-rich olivine with a P₂O₅ content up to 6.1 wt% from two samples from the Pine Canyon breccia pipe, Utah. The exact formation mechanism of this P-rich olivine remains unknown due to lack of outcrop source of its host rock (Agrell et al. 1998). The authors favored a disequilibrium formation mechanism for the P-rich olivine and interpreted that high-P₂O₅ content and low-silica activity are responsible for the formation of P-rich olivine. The third occurrence of P-rich olivine in terrestrial samples was found in two prehistoric ritual immolations in Tyro, Austria (Tropper et al. 2004; Schneider et al. 2013). These P-rich olivine grains are closely associated with phosphate minerals, containing up to 23 wt% P₂O₅. It was suggested that the formation of these P-rich olivine grains is related to partially melting and rapid, non-equilibrium crystallization of the precursor rocks with incorporation of chlorapatite, which supplied the phosphorus (Tropper et al. 2004; Schneider et al. 2013).

Two types of occurrences of P-rich olivine have been reported in extraterrestrial samples (Buseck 1977; Buseck and Clark 1984; Wasson et al. 1999; Sonzogni et al. 2009; Fowler-Gerace and Tait 2015; Wang et al. 2007). One is P-rich olivine (2–32 wt% P₂O₅) in pallasite meteorites (Buseck 1977; Buseck and Clark 1984; Wasson et al. 1999; Sonzogni et al. 2009; Fowler-Gerace and Tait 2015). Buseck (1977) suggested that the formation of P-rich olivine in pallasite meteorites should be due to replacement reaction with adjunct phosphates below the solidus. Recently, however, Fowler-Gerace and Tait (2015) proposed that the P-rich olivine in pallasite formed by extremely rapid crystallization from a melt. The other extraterrestrial P-rich olivine (0.2–3.9 wt% P₂O₅) was described in the altered opaque assemblages from the Ningshian carbonaceous chondrite (Wang et al. 2007). Wang et al. (2007) inferred that this P-rich olivine might have formed by non-equilibrium reaction between P-bearing molten metal and olivine crystals during rapid cooling. In summary, most of the natural P-rich olivine grains seems to be due to rapid