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Comment 2 on "Ultra-high pressure and ultra-reduced minerals in ophiolites may form by lightning strikes"

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Comment

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We read with great interest the paper by C. Ballhaus and coauthors (2017) reporting on electrical discharge experiments that showed how SiC and other phases found in mantle-derived rocks can potentially form by lightning strikes (Ballhaus *et al.*, 2017). The experiments are technically innovative and challenging and the results make fascinating reading. In a comment paper, Griffin *et al.* (2018) noted several lines of evidence that ultra-high pressure (UHP) and super reduced (SuR) minerals in ophiolites do not form by lightning strikes. Here, we add additional comments relating to the geological and mineralogical data from ophiolites that are not compatible with the model of Ballhaus *et al.* (2017).

(1) Not all of the samples of podiform chromitite and peridotite hosting UHP and SuR minerals were collected from surface outcrops exposed to lightning; many come from active mines 30-50 m below the surface, from the interiors of large blocks of ore, and/or from deep drill cores (Zhang *et al.*, 2016, 2017). Fulgurites are near-surface features, typically consisting of highly shattered and brecciated rock, which rarely extend more than a few meters below the surface. Furthermore, many of the same UHP and SuR minerals are routinely found in kimberlites sampled by deep mining operations (Shiryaev *et al.* 2011) leaving no question of their presence in the deeper mantle.

(2) Although lightning strikes can produce SuR minerals such as silicon carbide (moissanite), native metals and metal silicides (*e.g.*, Essene and Fisher, 1986; Rodgers *et al.*, 1989; Sheffer *et al.*, 2003), no UHP minerals have been reported from fulgurites; yet both moissanite and diamond grains occur together in ophiolite samples (Yang *et al.*, 2014, 2015a; Zhang *et al.*, 2016). These grains are mostly 200-300 µm in size and typically have euhedral to subhedral morphologies, whereas the experiments by Ballhaus *et al.* (2017) produced SiC crystals 100 times smaller, all of which are anhedral. *In-situ* diamonds in ophiolites are typically well-formed crystals enclosed in small (1 mm) spheres of amorphous carbon.

(3) No solid inclusions were reported from the minerals produced in Ballhaus' experiments, nor have mineral inclusions been reported in any known fulgurite phases. In contrast, diamonds in ophiolites contain a wide range of UHP and SuR mineral inclusions, including SiC, NiMnCo and other alloys, Mn-silicates (olivine, garnet), Mn-oxides, chromite and coesite; some even have fluid inclusions (Yang *et al.*, 2015a; Moe *et al.*, 2018; Wu *et al.*, 2017). These features are inconsistent with instantaneous shock metamorphism. Besides, there are well-documented exsolution lamellae of coesite and clinopyroxene in some chromite grains that require a high-pressure residence of SiO_2 in the grains (Yamamoto *et al.*, 2009), and this phenomenon should not be observed in fulgurite either.

(4) Barren, high-elevation terranes such as those in Tibet might be ideal locations for abundant lightning strikes, as suggested by Ballhaus *et al.* (2017), but there is nothing unique about the UHP and SuR occurrences in Tibet. These minerals have been confirmed in more than 10 different ophiolites in China, India, Russia, Myanmar, Albania, and Turkey, areas with different elevations and different climates (Yang *et al.*, 2015b; Das *et al.*, 2017; Lian *et al.*, 2017; Wu *et al.*, 2017).

The discovery of UHP and SuR minerals in rocks from the oceanic mantle has led to a variety of models for their formation (Arai *et al.*, 2013; Zhou *et al.*, 2014; Robinson *et al.*, 2015; Griffin *et al.*, 2016; Rollinson, 2016; Ballhaus *et al.*, 2017; Butler and Beaumont, 2017), none of which fully explain these occurrences. We emphasise that the presence of UHP and SuR phases in ophiolites is difficult to reconcile with the overwhelming geologic evidence that the host bodies form in the upper mantle. What now seems clear to us is that many ophiolites are bodies, which had a complex history involving subduction of crustal material at least to the transition zone, mixing of such material with mantle peridotites, partial melting and recrystallisation followed by upward migration to shallow levels where mantle slabs were trapped in suprasubduction zone wedges and modified by reaction with fluids and melts. The result is a mixture of crustal and mantle material which appears to exist metastably in ophiolitic chromitites and peridotites. Therefore, we do not consider lightning strikes to be an important source of UHP and SuR minerals in ophiolites, but the geologic processes leading to their formation are still poorly understood.

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