Depth of formation of super-deep diamonds: Raman barometry of CaSiO$_3$-walstromite inclusions

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ABSTRACT

“Super-deep” diamonds are thought to have a sub-lithospheric origin (i.e., below ~300 km depth) because some of the mineral phases entrapped within them as inclusions are considered to be the products of retrograde transformation from lower-mantle or transition-zone precursors. CaSiO$_3$-walstromite, the most abundant Ca-bearing mineral inclusion found in super-deep diamonds, is believed to derive from CaSiO$_3$-perovskite, which is stable only below ~600 km depth, although its real depth of origin is controversial. The remnant pressure ($P_{\text{inc}}$) retained by an inclusion, combined with the thermoelastic parameters of the mineral inclusion and the diamond host, allows calculation of the entrapment pressure of the diamond-inclusion pair. Raman spectroscopy, together with X-ray diffraction, is the most commonly used method for measuring the $P_{\text{inc}}$ without damaging the diamond host.

In the present study we provide, for the first time, a calibration curve to determine the $P_{\text{inc}}$ of a CaSiO$_3$-walstromite inclusion by means of Raman spectroscopy without breaking the diamond. To do so, we performed high-pressure micro-Raman investigations on a CaSiO$_3$-walstromite crystal under hydrostatic stress conditions within a diamond-anvil cell. We additionally calculated the Raman spectrum of CaSiO$_3$-walstromite by ab initio methods both under hydrostatic and non-hydrostatic stress conditions to avoid misinterpretation of the results caused by the possible presence of deviatoric stresses causing anomalous shift of CaSiO$_3$-walstromite Raman peaks. Last, we applied single-inclusion elastic barometry to estimate the minimum entrapment pressure of a CaSiO$_3$-walstromite inclusion trapped in a natural diamond, which is ~9 GPa (~260 km) at 1800 K. These results suggest that the diamond investigated is certainly sub-lithospheric and endorse the hypothesis that the presence of CaSiO$_3$-walstromite is a strong indication of super-deep origin.

Keywords: Diamond, inclusion, CaSiO$_3$-walstromite, micro-Raman spectroscopy, ab initio methods, elastic geobarometry

INTRODUCTION

Diamonds and the mineral inclusions that they trap during growth provide a unique window on the deep Earth. A small portion (~6%) of diamonds (Stachel and Harris 2008) are interpreted to crystallize between 300 and 800 km depth (Harte 2010) because some of the inclusions entrapped are considered to be the products of retrograde transformation from lower-mantle or transition-zone precursors. However, in many cases undisputed evidence of these purported high-pressure precursors as inclusions in diamonds is lacking, and, consequently, their real depth of origin has been proven only in rare cases (e.g., Brenker et al. 2002; Pearson et al. 2014). Most so-called “super-deep diamonds” contain mainly walstromite-structured CaSiO$_3$ (hereafter CaSiO$_3$-walstromite), ferropericlase ([(Fe,Mg)O]), enstatite (MgSiO$_3$), and jeffbenite [(Mg,Fe)$_2$Al$_2$Si$_4$O$_{12}$], a tetragonal phase with garnet-like stoichiometry previously known by the acronym TAPP (see Nestola et al. 2016), and it is through the study of these mineral phases that the depth of formation of super-deep diamonds can be retrieved.

CaSiO$_3$-walstromite is the dominant Ca-bearing phase in super-deep diamonds (Joswig et al. 1999), and in almost all cases it is considered the product of back transformation from CaSiO$_3$-perovskite, which is stable only below ~600 km depth within the regular high-pressure assemblage of peridotitic/eclogitic mantle rocks (Frost 2008; Kaminsky 2012). However, there is compelling evidence that at least some CaSiO$_3$-walstromite originate within the upper mantle (Brenker et al. 2005; Anzolini et al. 2016), although this would require a substantial change in the source rock chemistry. Assuming peridotitic/eclogitic mantle chemistries, CaSiO$_3$-perovskite is the main Ca-host in the lower mantle (Ringwood 1991), but is also present in the...