Origin of β-cristobalite in Libyan Desert Glass: The hottest naturally occurring silica polymorph?

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Abstract

Identifying and determining the origin of β-cristobalite, a high-temperature silica polymorph, in natural samples is challenging as it is rarely, if ever, preserved due to polymorphic transformation to α-cristobalite at low temperature. Formation mechanisms for β-cristobalite in high-silica rocks are difficult to discern, as superheating, supercooling, bulk composition, and trace element abundance all influence whether cristobalite crystallizes from melt or by devitrification. Here we report a study of β-cristobalite in Libyan Desert Glass (LDG), a nearly pure silica natural glass of impact origin found in western Egypt, using electron microprobe analysis (EMPA), laser ablation inductively coupled mass spectrometry (LA-ICP-MS), time-of-flight secondary ion mass spectrometry (ToF-SIMS), scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD). The studied grains are mostly 250 μm in diameter and consist of ~150 μm wide cores surrounded by ~50 μm wide dendritic rims. Compositional layering in LDG continues across cristobalite grains and mostly corresponds to variations in Al content. However, layering is disrupted in cores of cristobalite grains, where Al distribution records oscillatory growth zoning, whereas in rims the high Al occurs along grain boundaries. Cristobalite cores thus nucleated within layered LDG at conditions that allowed mobility of Al into crystallographically controlled growth zones, whereas rims grew when Al was less mobile. Analysis of 37 elements indicates little evidence of preferential partitioning; both LDG and cristobalite are variably depleted relative to the upper continental crust, and abundance variations correlate to layering in LDG. Orientation analysis of {112} twin systematics in cristobalite by EBSD confirms that cores were formerly single β-cristobalite crystals. Combined with published experimental data, these results provide evidence for high-temperature (>1350 °C) magmatic crystallization of oscillatory zoned β-cristobalite in LDG. Dendritic rims suggest growth across the glass transition by devitrification, driven by undercooling, with transformation to α-cristobalite at low temperature. This result represents the highest formation temperature estimate for naturally occurring cristobalite, which is attributed to the near pure silica composition of LDG and anomalously high temperatures generated during melting by meteorite impact processes.

Keywords: Cristobalite, silica, Libyan Desert Glass, EBSD, meteorite impact

Introduction

The high-temperature silica polymorph β-cristobalite is thermodynamically stable from 1470–1726 °C at 1 atm; however, it is metastable at lower temperatures (Swamy et al. 1994; Heaney 1994). The low-temperature polymorph α-cristobalite forms through displacive transformation below ~270 °C (Dollase 1965), and is thus the only form of cristobalite found in natural samples (cf. Keith and Muffler 1978; Damby et al. 2014). Occurrences of α-cristobalite (hereafter simply cristobalite) are restricted to volcanic glass (e.g., Swanson 1989; Watkins et al. 2009), volcanic ash and/or soils (Horwell et al. 2013), hydrothermal/diagenetic deposits (Dollase 1965; Shoval et al. 1997), and granulite facies rocks (Darling et al. 1997). The only other significant terrestrial occurrences of cristobalite are in high-temperature melt rocks, including those formed during meteorite impact (e.g., Ferrière et al. 2009; Trepmann et al. 2020), and less commonly, fulgurite (e.g., Crespo et al. 2009). Extraterrestrial occurrences of cristobalite include lunar basalts (e.g., Christie et al. 1971), martian rocks, including shergottites (Leroux and Cordier 2006) and nakhlites (Kuebler 2013), and diogenite meteorites (Benzerara et al. 2002). Here we describe a study to test formation hypotheses for cristobalite in Libyan Desert Glass (LDG).

Occurrences of LDG are found over several thousand km² in western Egypt. It consists of high-silica glass formed by fusion of a quartz-rich source, widely attributed to meteorite impact (e.g., Koeberl 1997, 2000; Koeberl and Ferrière 2019; Cavosie and Koeberl 2019; Svetsov et al. 2020). The LDG is yellow to green and translucent, although some pieces are dark and others milky.