Shocked quartz: A $^{29}$Si magic-angle-spinning nuclear magnetic resonance study

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ABSTRACT

Quantitative $^{29}$Si NMR spectra of single-crystal $\alpha$-quartz, shock compressed to 12±38 GPa and recovered, provide new information about the complex response of quartz to shock loading. Spectra from samples recovered from shock pressures of 12±20 GPa show a broadening of the $^{29}$Si NMR peak and the development of asymmetry toward lower NMR frequency (indicating an increase in the mean Si-O-Si intertetrahedral bond angle). NMR spectra of samples shock compressed above 25 GPa show increasing amounts of a separate amorphous phase of SiO$_2$ with a mean Si-O-Si bond angle roughly 5° narrower, and 10–15% denser, than fused SiO$_2$. Small amounts of crystalline material remain with a mean Si-O-Si bond angle up to 3° larger than unshocked $\alpha$-quartz. The recovery of dense glass indicates that post-shock temperatures were sufficiently low to also preserve stishovite, had any been created in our experiments. The paucity of stishovite or $^{26}$Si in an amorphous phase in our recovered samples suggests that the formation of stable, high-coordinated Si is kinetically hindered in shock compression experiments up to about 35–40 GPa, except in regions of high temperature, such as planar deformation features (PDFs), microfaults (pseudotachylites), or voids.

INTRODUCTION

For nearly 40 years, physicists, chemists, and mineralogists have studied quartz recovered from shock experiments in an effort to understand the behavior of silicates during shock compression and release. Although shock recovery experiments are limited in pressure, can produce complicated stress histories, and preserve only the structural changes that can be rapidly formed and quenched, these studies have nevertheless improved our understanding of the effects of shock waves on solids and have been applied to a diverse set of problems including modeling of impact and explosion cratering and the unambiguous identification of meteorite impact craters. However, our understanding of the behavior of quartz under shock loading is still evolving.

DeCarli and Jamieson (1959) reported that quartz shocked to 60 GPa became amorphous. Wackerle (1962) published equation-of-state data for quartz shocked up to 60 GPa and noted a kink in the Hugoniot suggesting a phase transition over the shock pressure range of 14–35 GPa. A note added in proof mentions the discovery of stishovite and suggests that it may be the shock-induced high-pressure phase suggested by the Hugoniot data. McQueen and coworkers (1963) proposed that quartz transforms directly to stishovite, or a stishovite-like amorphous material during shock compression to 20–35 GPa remains a widely held view, and numerous shock experiments on quartz or amorphous SiO$_2$ at pressures >40 GPa have assumed to be studying stishovite or a material thermodynamically equivalent to stishovite (e.g., McQueen et al. 1963; Davies 1972; Grady et al. 1974; Lyzenga et al. 1983; Schmitt and Ahrens 1989). The recovery of trace quantities of stishovite in shock experiments is cited as evidence of this phase transformation.

Microscopic analyses of shocked quartz from experiment and nature suggest a more complicated set of phenomena than a simple solid-state phase transformation of quartz to stishovite or an amorphous material with Si in sixfold coordination. Stishovite observed in quartz experimentally shock recovered from pressures >20 GPa is found mainly associated with planar deformation features (PDFs), voids, or pseudotachylites (microfaults)-sites of intense local heating (e.g., Goltrant et al. 1991; Goltrant et al. 1992; Gratz et al. 1992). Similarly, stishovite found in shocked quartz from impact craters is also generally associated with PDFs, voids, or pseudotachylites (e.g., Stöffler 1971; Kieffer 1971; Kieffer et al. 1976; Martini 1991).

In this paper, we present $^{29}$Si NMR analyses of single

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