Mineralogical and isotopic effects of shock wave thermal histories on chondrule precursors

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Introduction: Nebular shock waves may be a heat source for chondrules [1, 2, 3]. Because of a lack of isotopic evidence for evaporation, chondrules may have formed at high dust enrichments, leading to shock wave thermal histories with higher heating and cooling rates, and higher pre-shock and peak Ts than otherwise. To stabilize the relatively high FeO contents of Type II chondrules, high water enrichments are needed, leading to higher peak Ts and lower cooling rates [4]. Here, a kinetic model for evaporation and recondensation, based on metal-silicate, liquid-crystal phase relations of MELTS [5], is applied to the chemical and isotopic evolution of chondrule precursors in dust- and water-enriched systems subjected to shock waves modeled at high spatial resolution, using a Hertz-Knudsen equation modified to account for thermal disequilibrium between condensate and gas [6].

Technique: Because of the Fe/Si depletion in Types I and II chondrules [7], precursors of chondritic composition except for Fe/Si=0.10x and 0.33xCI, resp., were assumed, both initially equilibrated at log f_{O2}=IW-2.6. Calculations start at 1400K, where 75% of the solid, non-metallic fraction is assumed isolated from the remaining, equilibrated fraction. Melting kinetics are treated as in [8], using the partial molar Gibbs energy of each solid in the multicomponent liquid to calculate its free energy of fusion. Fractional crystallization was modeled using curves in Fig. 1, derived from histograms of olivine X_{Fa} that we measured in run products from [9] obtained on a Type II chondrule composition cooled at 10 and 100 K/hr. Evolution of chondrule precursors is tracked continuously before and after complete evaporation and recondensation of FeO and alkalies by switching between activity-composition relations of MELTS and those of CMAS [10].

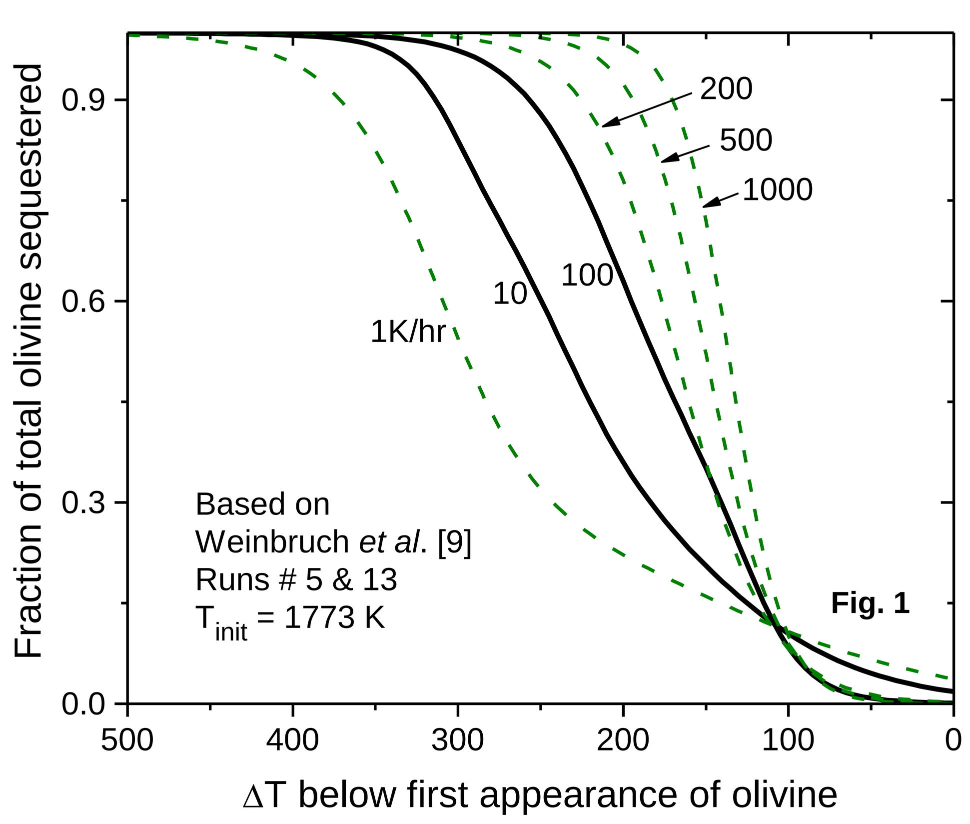


Fig. 1

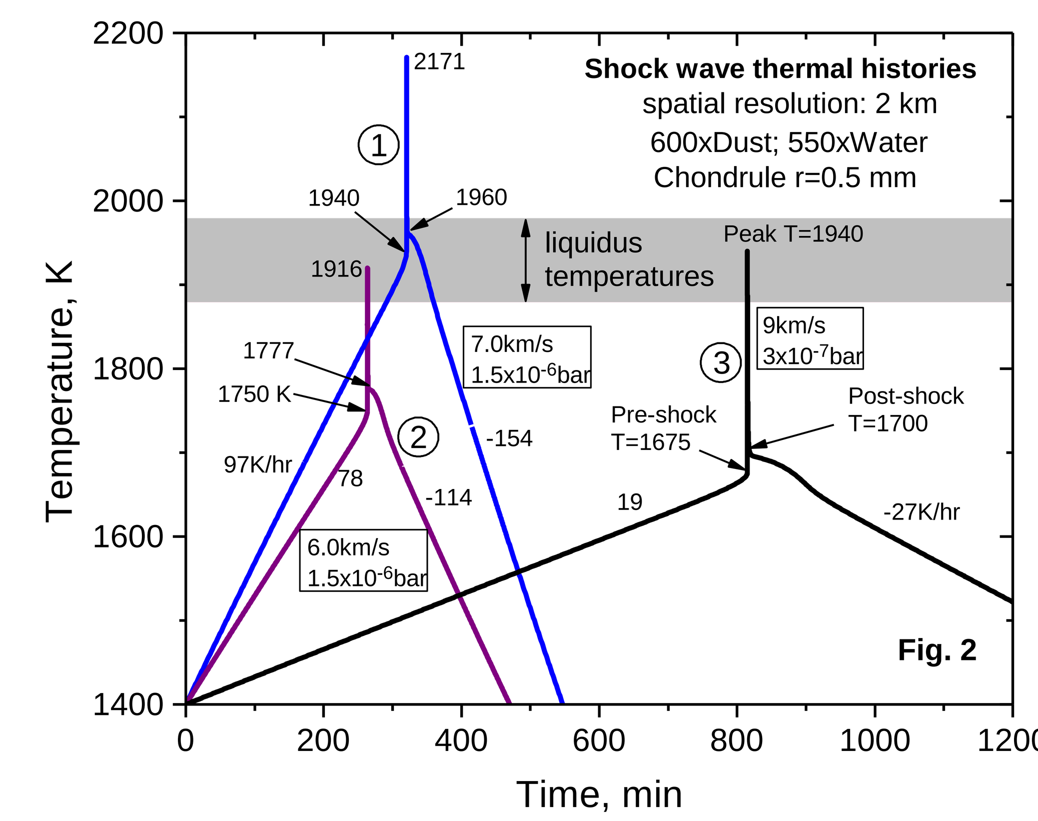
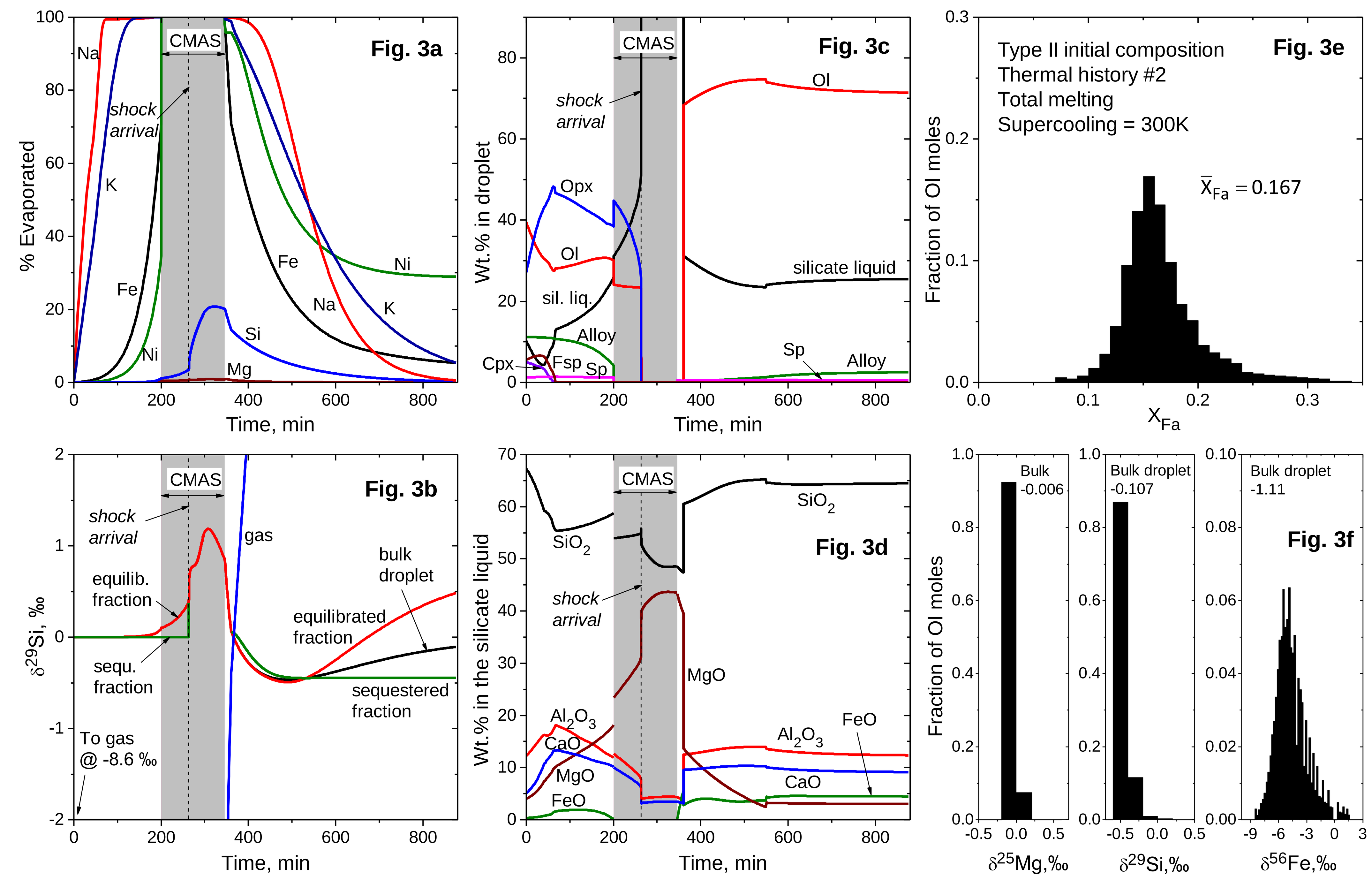
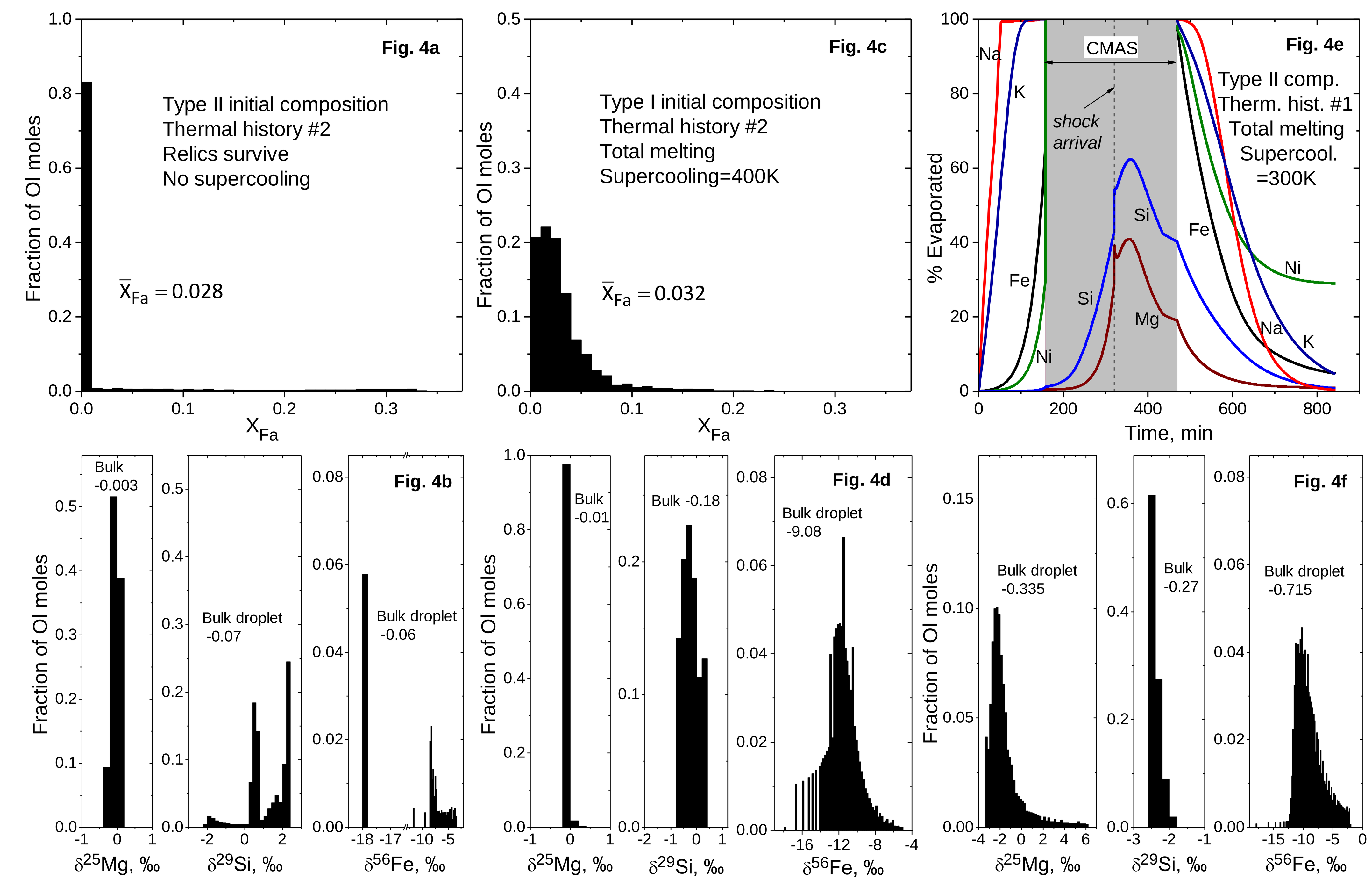


Fig. 2

Results: Computed shock wave thermal histories (Fig. 2) for systems enriched 600xsolar in dust and 550x in water yield log f_{O2}~IW-1.4 in the ambient gas. As T increases, amounts of sequestered and equilibrated silicates and oxides decrease and liquid increases at rates governed by melting kinetics; closed-system evaporation occurs at rates governed by experimentally determined evaporation coefficients and liquid surface area; and metallic Fe disappears by evaporation, and by oxidation by the surrounding water-rich gas on a time-scale assumed comparable to the chondrule evolution time. Although the peak T is superliquidus, the T spike lasts for only 1-2 minutes, so cases studied assumed (a) total melting, followed by various amounts of supercooling, or (b) survival of 5% relict olivine with no supercooling. Hence, recondensation occurs at various times relative to fractional crystallization. Histograms of X_{Fa} and olivine isotopic composition contain relics that survived heating, and grains that fractionally crystallized during cooling. Results for a Type II initial composition subjected to thermal history #2 (Fig. 2) are shown in Fig. 3. Total melting and supercooling of 300K were assumed, such as might yield a BO texture. All iron vaporizes (Fig. 3a). Because of supercooling, fractional crystallization of olivine begins during FeO recondensation, yielding an X_{Fa} histogram like a Type II chondrule (Fig. 3e) and preserving a wide range of δ^{56}Fe (Fig. 3f). If olivine relics survive, preventing supercooling and allowing a PO texture to form, olivine crystallizes before most Fe recondenses, and is almost all forsterite (Fig. 4a) with a wide range of δ^{29}Si (Fig. 4b). When a Type I composition experiences the same thermal history (#2), melts totally and





supercools by 400K, an X_{Fa} histogram like that of a Type I chondrule (Fig. 4c), and a wide range of δ^{56}Fe (Fig. 4d), are seen. When a Type II starting composition experiences the higher T of thermal history #1 (Fig. 2) and supercools by 300K, much more evaporation occurs (Fig. 4e), yielding wide ranges of δ^{25}Mg, δ^{29}Si and δ^{56}Fe (Fig. 4f).

Conclusions: In all cases studied, shock wave thermal histories for dust- and water-enriched systems cause total evaporation of oxidized and metallic Fe from chondrule precursor compositions.

- If nuclei survive shock heating, thus preventing supercooling and allowing PO textures, most olivine crystallizes before FeO recondensation, and neither Type I nor Type II fayalite histograms can be produced.
- If no nuclei survive, resulting in supercooling and BO textures, fayalite histograms typical of Types I and II chondrules can be produced at a single log f_{O2} (IW-1.4) from bulk compositions with Fe/Si ratios characteristic of each type.
- In the latter cases, fractional crystallization occurs during FeO recondensation, creating large internal δ^{56}Fe heterogeneities that have not been observed in chondrules.

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