
Exsolution lamellae in rock-forming minerals commonly constitute the only recognizable record of the thermal history of the host rock. It is important, therefore, that they are interpreted correctly. Although great advances have been made in understanding the influence of both equilibrium phase relationships and the crystallographic aspect of exsolution phenomena in the pyroxenes (eg. 1), exsolution intergrowths in pyroxenes are usually interpreted in terms of a single thermal cycle. This may well be warranted for most terrestrial pyroxenes because they have rarely been subjected to more than one thermal cycle without recrystallization and reequilibration (eg. in a thermal aureole or through regional metamorphism). However, it is generally accepted that virtually all the returned lunar samples have been subjected to one or more shock events which cover a wide range of shock intensity, although some samples show little petrographic evidence of shock. Furthermore, it is known that many lunar rocks were subjected to shock-related adiabatic heating and that in some samples the temperatures achieved were demonstrably greater than 1550°C (2). Although shock-induced temperatures above 1100°C will usually result in partial to complete melting, it follows that many if not most lunar minerals must have been subjected to shock-related subsolidus heating and cooling. The questions that must be considered with respect to lunar samples are (1) is it possible to effect exsolution in complex solid solutions, such as pyroxenes, by means of the transient subsolidus thermal effects associated with a shock event, and (2) if exsolution does occur in a thermal cycle of such relatively short duration, would it be possible to differentiate between exsolution lamellae developed through relatively slow cooling in an original igneous rock and overprints of shock-related exsolution lamellae. These are not solely hypothetical questions inasmuch as complex exsolution relationships in lunar pyroxenes which are difficult to interpret on the basis of a single cooling cycle have been found through optical and electron microprobe studies (3,4). We have attacked the first question in a relatively simple system through an electron-optical study of an experimentally shocked ilmenite-hematite solid solution (5).

Hemoilmcnic (Fe,Mn) from Ilmen Mountains, U.S.S.R. (U.S. Nat. Mus. No. 96189) was found to be chemically and physically homogeneous by a combination of reflected-light microscopy, electron microprobe analysis, transmission electron microscopy of ion-thinned foils, and X-ray powder diffraction analysis; however it does contain Mn, Mg, and Nb (5). A particulate sample of this ilmenite was shock-loaded under a positive pressure of argon at a peak pressure of 75 kb using chemical explosives. The coherent product showed strong development of several sets of shock-induced twin lamellae in polished section but was otherwise optically homogeneous. However, transmission electron microscopy of ion-thinned foils showed that subsolidus unmixing of hematite on a sub-optical scale had occurred in response to the shock event. The hematite platelets are epitaxially oriented on the (0001) plane of the
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host ilmenite, but are not detectable by either X-ray powder diffraction or optical microscopy because they have a maximum diameter of 5000Å and a maximum thickness of 500Å. We have shown further, by transmission electron microscopy that the ilmenite deformed in response to the shock event by two discrete sequential deformation modes. It deforms first by multiple twinning parallel to (0001) and then by multiple twinning on rhombohedral planes. The first deformation mode is apparently dominant at high strain rates and relatively low temperatures and constitutes a shock-recognition criterion for ilmenite; the latter deformation mode appears to be dominant at the lower strain rates and relatively high temperatures which prevail during post-shock adiabatic expansion and heating and corresponds to the deformation mode of tectonically deformed ilmenite. Our results clearly show that the unmixing of hematite in the shock event occurred either during or more likely after the development of the basal-plane twins but before the development of the rhombohedral twins. The unmixing may result from post-shock heating which could provide the energy for diffusion; the rhombohedral twins probably developed as a result of post-shock decompression and thermal stresses.

In order to determine whether unmixing in the ilmenite occurred when shock waves were propagated through it or whether unmixing occurred in response to post-shock adiabatic heating and cooling, samples of the unshocked homogeneous ilmenite were heated in evacuated silica tubes (with and without iron present) in the temperature range 380°-1000°C for one week and then quenched in water. All products examined thus far were optically homogeneous and untwinned. However, transmission electron microscopy of ion-thinned foils reveals the presence of unmixed oriented hematite platelets (sub-optical size range < 1 μ) in an untwinned ilmenite matrix. The size, shape, and orientation of the precipitate phase is identical with that observed in the experimentally shocked ilmenite. These results strongly indicate that the unmixing of the ilmenite-hematite solid solution was the result of the post-shock adiabatic thermal cycle.

This study shows that it is possible to unmix a solid solution as a result of the thermal effects of a shock event. One must be cautious, therefore, before interpreting exsolution phenomena in lunar rock-forming minerals on the basis of a simple model which involves a single cycle of crystallization, cooling, and subsolidus unmixing.

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Fig. 1. Transmission electron micrograph of ion-thinned foil of ilmenite heated at 380°C for one week showing exsolved oriented platelets of hematite.