Is the olivine-spinel phase transformation martensitic?

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Olivine, the dominant mineral in the Earth's uppermost mantle, undergoes one, or possibly a series of phase transformations to adopt a spinel structure at pressures above ~13 GPa. The mechanism by which the transformation is accomplished could have important implications for understanding mantle dynamics and deep focus earthquakes. Recently, it has been proposed that the transformation may proceed by a martensitic mechanism. We discuss here the characteristic properties of martensitic transformations and present evidence that the analogous transformation in Mg$_2$GeO$_4$ does not proceed by such a process.

Polymorphic transformations which occur by a martensitic mechanism involve a specific, coordinated movement of atoms. The interface which effects the transformation propagates by the movement of a series of partial dislocations resulting in the production of stacking faults. Such faults represent monolayers of the new phase. This process contrasts with the nucleation and growth mechanism in which the interface propagates by a generally uncoordinated, thermally activated movement of atoms. Martensitic transformations involve a significant shear component in their transformation strain. This means that if the transformation is accomplished under nonhydrostatic stress, the process should be enhanced in favourably oriented parent crystals and retarded in unfavourably oriented parents. Higher stresses (and hence strain rates) will favour the transformation. The daughter phase generally grows as lamellae in the parent, whereas the nucleation and growth mechanism usually produces irregular interfaces due to more rapid migration in directions of greater stored strain energy in the deformed parent. Martensitic mechanisms always exhibit specific crystallographic relationships between parent and daughter crystals, whereas nucleation and growth (also proposed for olivine-spinel) can, but normally does not, produce such relationships. The topotactic relation required by the martensitic mechanism proposed for the olivine-spinel transformation is $[100]_\text{w}$ parallel to $(111)_\text{w}$, and $(001)_\text{w}$ parallel to $(011)_\text{w}$ (refs 3, 4). This crystallographic relationship has been reported in a few instances in Fe$_2$SiO$_4$ (ref. 3) and Ni$_2$SiO$_4$ (ref. 5); in the latter case only $\frac{3}{2}$ out of 10 spinel crystals showed the exact relationship, and 5 showed large deviations. A occasional presence of topotaxy is compatible with any transformation mechanism, but it must be present in all instances to support the martensitic mechanism.

The olivine-spinel transformation for the chemical composition approach for the Earth's mantle, (Mg$_{0.6}$Fe$_{0.4}$)$_2$SiO$_4$, has been very difficult to study directly due to the very high transformation pressure$^{8,9}$. Consequently, the transformation has been studied in other systems, principally Fe$_2$SiO$_4$ (ref. 3), Ni$_2$SiO$_4$ (ref. 5) and Mg$_2$GeO$_4$ (ref. 10), which undergo the transformation at lower pressures. Although systematic studies of these and other analogous systems have shown very great similarities between the various systems (one, some complication remains. Each of the analogue systems listed above undergoes the transition directly, whereas the Mg-rich silicate olivine system there is another ($\beta$) phase with a distorted-spinel structure which is found at intermediate pressures$^{10}$. Transmission electron microscopy (TEM) studies$^{2,11}$ indicate that in many cases the $\beta$-phase may be a quench product formed at the expense of the $\gamma$-phase. Considering these uncertainties, the simplest approach regards the direct transformation ( Olivine-spinel) as relevant to the mantle$^{12}$. The martensitic mechanism was proposed on this basis and the totopatotic relations found in Fe$_2$SiO$_4$ and Ni$_2$SiO$_4$ have been cited as support for the martensitic mechanism on the same basis. We continue this approach here while recognizing that the question of relevance to the mantle remains unresolved until the mineralogy is better known.

To test the martensitic hypothesis, we selected a deformed Mg$_2$GeO$_4$-olivine sample which had partially transformed to spinel. The run conditions of this creep experiment (no. 92) were: confining pressure, $P = 1.3$ GPa; average differential stress, $\sigma = 280$ MPa; total axial strain, 5%; duration 55 h (ref. 11). The temperature along the 18.4-mm long sample varied from 950 °C at the lower end to 1,200 °C in the centre. Thus, the lower portion of the sample was well within the spinel field but the central portion was just inside the olivine field. Specimens were selected from a small region of 50–60% spinel near the lower end of the sample. TEM foils were prepared by

![Fig. 1 High-voltage transmission electron micrograph of large spinel grains with a high density of stacking faults and parent olivine with moderate dislocation density (800 kV). The maximum compressive stress applied to the specimen lies NE-SW, parallel to the spinel-spinel grain boundaries.](image-url)
We have failed to find any evidence indicative of martensitic transformation. On the other hand, the observation that the spinel displays a strong growth anisotropy reflecting the stress field is an interesting new discovery. This is consistent with a simple nucleation and growth mechanism in which the driving force for growth varies with the $P\Delta V$ term in the equation describing the difference in Gibbs free energy between the two phases (ref. 16, and work in preparation).

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**Noise in chaotic systems**

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Procedures which estimate the noisiness of complicated, aperiodic data are outlined here and considered in the context of transitional fluid flow, although similar questions arise in many other fields. Because this is the initial formulation of these ideas only qualitative results are presented; any attempt to develop quantitative measures of randomness will be postponed until more testing and refinement of the procedures have been completed.

Consider a fluid experiment such as Rayleigh–Bénard convection or the flow between concentric cylinders in a regime which produces aperiodic flow. Substantial theoretical and experimental attention has been given to the temporal characteristics of these flows as dynamical systems. The Landau–Hopf model of turbulence portrays turbulent flow as quasiperiodic with many independent frequencies. This view was successfully challenged by Ruelle and Takens with an argument based on the structural instability of quasiperiodic attractors for dynamical systems. Extensive high-precision experiments have demonstrated that the transition to aperiodic flow occurs directly from flows whose power spectra have few independent frequencies. These measurements for small aspect ratio fluid experiments are evidence that fluid transitions in this regime are described reasonably well by the bifurcations of systems of differential equations with few degrees of freedom. There is still disagreement, however, as to whether the aperiodicity of the posttransition flows has the characteristics which one finds in a trajectory of a system of ordinary differential equations with a state space of low dimension. In particular, it has been suggested that some aspects of the data are described much better by stochastic models. The methods proposed here may help resolve this matter.

Dynamical systems with few degrees of freedom can have 'strange attractors': bounded sets of aperiodic trajectories which are asymptotically stable. Some features of a trajectory in...