Oscillatory zonation of minerals and self-organization in silicate solid-solution systems: a new nonlinear dynamic model

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Abstract: A new non-ideal, disequilibrium and nonlinear dynamic model is presented to describe the process of crystal growth in the melt

\[ f = \frac{1}{[1 + (\beta/X')(1-X') \exp(-W/RT)(1-2f)]} \]

where \( f \) and \( X' \) are, respectively, the mole fractions of a component in the crystal and melt at the interface, \( W \) the total interchange energy, \( R \) the gas constant, \( T \) temperature and \( \beta = k_b/k_A \), with \( k_A \) and \( k_B \) representing the rate constants of components A and B. Results of the numerical simulation of this model demonstrate that a domain of triple-valued compositions exists if \( W/RT < -2 \). Together with mass-balance equations, this model explains satisfactorily the oscillatory zonation patterns in silicate solid-solution systems, indicating that self-organization is responsible for the development of such profiles during crystal growth.

Key-words: oscillatory zoning, self-organization, silicate solid-solution systems, nonlinear dynamics, multiple valuedness.

1. Introduction

Interest in the formation of repetitive non-inherited compositional zoning patterns in rocks and minerals dates back to Knopf (1908), Liesegang (1913, 1915) and Hedges & Myers (1926), whose investigations provided qualitative descriptions of ordered phenomena. Quantitative studies of geological systems and processes have traditionally concentrated on equilibrium systems and reversible reactions. More recently, research has been increasingly focused on disequilibrium phenomena, although it was limited within the linear range of disequilibrium thermodynamics where the rates of irreversible processes are linear functions of the thermodynamic forces (e.g., Fisher, 1973; Joesten, 1974; Atherton, 1976; Cygan & Lasaga, 1982).

Since the 1980s, however, nonlinear disequilibrium phenomena in geological systems have received the attention of many geologists (e.g., Haase et al., 1980; Allègre et al., 1981; Ortoleva et al., 1987; Yu, 1987; Yu & Jiang, 1990; Wang & You, 1988; Wu & Wang, 1990; Wang, 1991; Jamtveit, 1991). The most noteworthy characteristic of far-from-equilibrium systems is their potential to create temporal-spatial patterns (dissipative structures) through an amplification of small fluctuations in the system (Nicolis & Prigogine, 1977).

The most striking example of nonlinear phenomena is oscillatory zoning in plagioclase, which may exhibit ten or more complete compositional oscillations or small-scale periodic compositional variations superimposed on large-scale but less regular compositional changes (Downes, 1974; Sibley et al., 1976; Allègre et al., 1981; Lasaga, 1982; Simakin, 1983; Boudreau, 1984). As another example, a regular alternation may be commonly observed between two minerals in skarns (Guy, 1981). A further example is provided