Minor- and trace-element sector zoning in synthetic enstatite

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ABSTRACT

Minor- and trace-element sector zoning is nearly ubiquitous in pyroxene grown from basaltic melts using 1 atm gas-mixing furnaces. Mineral/melt partition coefficients can differ between sectors by more than a factor of five. A synthesized hypersthene-normative basalt composition was doped with Al, Cr, and Ti using a matrix of doping experiments, to understand better the mechanisms behind the formation of sector zoning. Isothermal and controlled-cooling experiments were conducted. The \{010\} sectors contain higher enrichments of Al, Cr, and Ti than \{100\} sectors, at the expense of Mg and Si. Evaluation of these relative sector enrichments indicates that sector zoning results from several kinetic mechanisms, which exert influence even when attempting laboratory conditions that approximate equilibrium: (1) rapid growth rate, not necessarily synonymous with rapid cooling; (2) crystal-chemical control by means of charge-coupled substitutions; and (3) diffusion limitations of Si tetrahedra in the melt boundary layers respective to the different crystal faces.

Keywords: Enstatite, sector zoning, charge-coupled substitution, kinetic mechanisms, crystal growth

INTRODUCTION

The sector zoning of major, minor, and trace elements that occurs in staurolites and pyroxenes has been recognized for more than 35 years (Hollister and Bence 1967; Hollister 1970; Hargraves et al. 1970; Hollister and Hargraves 1970; Hollister et al. 1970; Hollister and Gancarz 1971; Nakamura 1973; Downes 1974; Dowty 1976, 1977; Harkins and Hollister 1977; Shimizu 1981; Larsen 1981; Shearer and Larsen 1994; McKay et al. 1986; Watson and Liang 1995; Watson 1996; Steele et al. 1997). Consideration of sector zoning contributed important insights into the petrogenesis of lunar samples. For example, the presence of sector zoning in lunar basalts conclusively demonstrated that (1) the high-Al content of lunar basaltic pyroxenes was not due to growth at high pressure; (2) the irregular optical extinction patterns of lunar pyroxenes were not due to realignment of crystal structures by impact shock; and (3) lunar pyroxenes grew entirely at the lunar surface where wholly liquid lavas quenched (Hollister and Hargraves 1970; Hargraves et al. 1970; Hollister et al. 1971). Moreover, Watson (1996) demonstrated theoretically that one should expect sector zoning more often than reported. Nevertheless, sector zoning generally seems to be largely ignored or regarded as an uncommon phenomenon without much petrologic significance. Perhaps this is due, as Steele et al. (1997) highlight, to the difficulty in observing sector zoning. They show how cathodoluminescence can be used to detect sector zoning, but more importantly reemphasize how sector zoning can be used to distinguish between petrogenetic hypotheses, as originally demonstrated with the lunar pyroxenes (Hollister and Hargraves 1970; Hargraves et al. 1970; Hollister et al. 1971). The presence of sector zoning reflects the influence of kinetic mechanisms during crystallization (Hollister and Bence 1967). Investigation of sector zoning should improve our understanding of these mechanisms.

Digital mapping of X-ray intensities measured by wavelength-dispersive methods using the latest generation of electron microprobes has revealed that sector zoning of minor and trace elements is nearly ubiquitous in synthetic pyroxenes (Schwandt and McKay 1995). We are discovering that minor- and trace-element sector zoning are present in most synthetic samples, even in pyroxenes that are formed under experimental conditions as close to theoretical equilibrium as is possible to attain in the laboratory (isothermal). In fact, sector zoning of minor and trace elements appears to be the normal mode of crystallization, rather than the exception, for rapidly grown crystals. In isothermal experiments, the presence of sector boundaries diminishes during crystal growth, but can be reinitiated by imposing a step decrease in the crystallization temperature, i.e., increasing the amount of supercooling. Only with especially long experiment lengths (several weeks) do the sector-zoning boundaries disappear with continued mineral growth, as mineral growth slows. However, it is important to clarify that the cores of crystals remain sector zoned, even though more slowly grown rims are compositionally more uniform. This finding indicates that the mechanism for sector formation is controlled by growth rate, and the crystal does not re-equilibrate by volume diffusion.

Prior to the availability of high-sensitivity digital element mapping (Fig. 1), minor-element (Al) sector zoning could not be visualized with back-scattered electron imaging or X-ray dot maps recorded on film. Steele et al. (1997) demonstrated that cathodoluminescence can be used to identify sector zoning. However, even with digital imaging, the visualization of minor-element sector zoning is hampered because randomly cut crystals do not easily reveal it. Only crystals that are sectioned