Olivine from planetary basalts: Chemical signatures that indicate planetary parentage and those that record igneous setting and process

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ABSTRACT

The systematics of Mn-Fe, Ni-Co, Ti, Cr, and V in olivine from 13 basalt suites from the Earth, Moon, and Mars were studied by electron and ion microprobe techniques. The results demonstrate that chemical signatures in olivine can be related to: (1) planetary parentage, where differences are the result of initial accretional ratios, source compositions, and oxygen fugacity; and also (2) igneous setting and process, where differences among basalt suites within a planet are a consequence of specific redox conditions in tectonic settings, differing melt compositions, and changes in element partitioning resulting from crystallization sequences and mineral modes. Manganese-Fe systematics indicate planetary parentage where the Mn/Fe ratio in olivine increases with increasing distance from the Sun (with the exception of the Moon, which can be explained). This sequence could be the result of initial Mn/Fe accretional ratios from the start of the solar system. Igneous processes such as differing melt compositions and crystallization sequences cause differences in the Mn/Fe ratios of olivine in basalt suites from the same planet. Nickel-Co and Ti systematics show that planetary signatures result from source-region differences among the three planets. For example, the lunar source regions are depleted in Ni and enriched in Ti, as compared with the Earth and Mars, and these characteristics are reflected in the olivine compositions. The differing partitioning behavior of Ni, Co, and Ti in planetary olivine suites is a result of crystallization sequences and initial melt compositions of the basalts during crystallization. Chromium concentrations in olivine result from differing oxygen fugacities and phase stabilities in the source regions of the three planets, whereas V concentrations in olivine are mostly a consequence of the different overall redox conditions on planetary bodies. Both Cr and V show igneous process signatures owing to different melt compositions, crystallization sequences, and modal mineralogy. Perhaps the most important conclusion from this study is that olivine in planetary basalts records information not only about igneous setting and process but planetary parentage as well, making the study of comparative planetary mineralogy an exciting way to gain new insights into basalt petrogenesis.

INTRODUCTION

Basaltic volcanism is a fundamental process that has occurred on the Earth, Moon, Mars, and asteroids (especially 4 Vesta), from the beginning of the solar system at 4.56 Ga, to the present time. As partial melts of planetary interiors, basalts have compositions that are the product of many physical and chemical factors including the thermodynamic history of a planet, composition and mineralogy of the planet’s interior, and post-extraction processes (Bence et al. 1980, 1981). Ultimately, many of these factors may be related to the origin and early evolution of the planetary body. Several comparative planetology studies have concentrated on the bulk-rock major-, minor-, and trace-element chemistry of basalts to understand differences among basaltic systems, the influences of a planetary environment on a basalt system, and chemical fingerprints of planetary mantles (Consolmagno and Drake 1977; Stolper 1979; Bence et al. 1980, 1981; Drake et al. 1989; Goodrich and Delaney 2000). This method works well when the basalts represent liquids erupted onto a planetary surface with little loss or gain of material (assimilation and/or cumulate processes). Other studies have recognized that the compositions of the silicate phases in basalts reflect differing chemical and physical conditions of the melts from which they crystallized, and therefore they are recorders of the processes that affect basaltic magmatism. These studies have demonstrated the usefulness of major and minor elements in the silicate phases of planetary basalts to understand similarities and differences in a comparative planetology context (e.g., Papike 1981, 1998; Papike 1996). We now extend this philosophy to a systematic study combining major-, minor-, and trace-element data to correlate chemical trends in basaltic silicate minerals with planetary origin and setting. This paper reports the composition of olivine grains from 13 planetary basalt suites, relating the similarities and differences to the effects of igneous process, and possible early solar system differentiation processes. This paper is the first of a three-part study; the second and third parts will examine chemical signatures in feldspar and chromite from planetary basalts.

We decided to concentrate on the chemistry of individual