The effects of contrasting Ti and Al activities on Mn/Fe systematics in pyroxene from lunar mare basalts

JAMES J. PAPIKE1, STEVEN B. SIMON1,*, AND CHARLES K. SHEARER1

1Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, U.S.A

ABSTRACT

The usefulness of the Mn/Fe ratios of olivine and pyroxene to identify a sample’s host parent body is well established. Although there is an overarching, defining slope for each planetary body, there is some scatter, or “dispersion” around the defining slope. This dispersion reveals important facts relating to the planetary body. The source regions of the three main types of lunar basalts (very high-Ti, low-Ti, and very low-Ti) have $f_{O_2}$ values near IW-1 or below, and all iron is either ferrous or metallic. The dispersion in the Mn/Fe ratios of pyroxene from the Moon is largely caused by differences in the Ti and Al concentrations in the mantle source regions and the resulting differences in Ti activity of the primary basaltic melts derived from those sources. Ti displaces ferrous iron in the pyroxene M1 site (in a coupled substitution with Al for Si in the tetrahedral site), and therefore, with increasing Ti activity the Mn/Fe ratio in pyroxene increases in all three suites studied. For lunar mare basalts, the effect of Ti activity on the occupancy of the pyroxene M1 site, and crystallization sequence differences among high-Ti, low-Ti, and VLT basalts account for almost all of the observed dispersion in the Mn/Fe ratios.

Keywords: Pyroxene, basalt, manganese, iron, titanium, aluminum

INTRODUCTION

Papike et al. (2003) introduced a technique where the Mn/Fe ratios of olivine or pyroxene and the anorthite content of plagioclase provided a tool to identify the planetary parentage of newly discovered meteorites. A recent paper (Papike et al. 2017) refined this technique, focusing on the angrite meteorites, and a new, robust determinative curve was obtained. On a plot of Mn vs. Fe cations per formula unit for olivine from basalts, the slopes of the data trends decrease in the sequence Mars, Earth, angrite parent body (APB), and Moon. Vesta was not included in the olivine discussion because basalts from Vesta (eucrites) have little or no olivine. For pyroxene, the decreasing Mn vs. Fe slope sequence is Vesta, Mars, Earth, and Moon. Analyses of angrite pyroxenes are not directly comparable to those from the other bodies because in angrite pyroxenes the M2 sites are completely filled by Ca (e.g., Mittlefehldt et al. 1998; Papike et al. 2016) and therefore have different substitution systematics.

Papike et al. (2017), however, did not discuss why we can compare relatively simple, small bodies such as the Moon, Vesta, and the angrite parent body, to much larger parental bodies (for example Earth and Mars) that have undergone complex evolutionary histories including core formation, magma ocean generation, and serial magmatism, yielding a range of basalt compositions exposed to a large, dynamic range of oxygen fugacity, from three log units below the iron-wüstite buffer to two log units above.

Data for pyroxene from high-Ti, low-Ti, and L-24 VLT basalts were taken from the literature (Papike et al. 1976, 1998; Vaniman and Papike 1977; Coish and Taylor 1978) and are tabulated in Supplemental Tables A1–A3. The L-24 data were incorporated into this study to examine the potential variability in mantle Mn/Fe outside of the PKT. The A-17 VLT basalts considered here are those studied by Wentworth et al. (1979). New analyses of pyroxene in these VLT samples (Supplemental Materials S1’ and A4) were obtained with a JEOL 8200 fully automated electron microprobe at the University of New Mexico, operated at 15 kV. Counting times on peaks ranged from 10 to 30 s; background count times equaled the peak counting times for each analysis. Pure oxide, synthetic glass, and natural mineral standards were used. Average relative errors are ~6% for Ti and Mn, 2% for Al, and 0.5% for Fe. Fits to the data, both linear and polynomial, were generated by curve-fitting algorithms built into the analysis. Pure oxide, synthetic glass, and natural mineral standards were used. Average relative errors are ~6% for Ti and Mn, 2% for Al, and 0.5% for Fe. Fits to the data, both linear and polynomial, were generated by curve-fitting algorithms built into the analysis.