

OLIVINE BAROMETRY: APPLICATION TO PRESSURE ESTIMATION FOR TERRESTRIAL AND LUNAR ROCKS. A. A. Finnerty, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; and S. M. Rigden, Dept. Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

Knowledge of temperature at even a single depth within the interior of a planetary body can place valuable constraints on the thermal state of that body. To that end, the efforts of many people have been directed towards calibration and application of geothermometers and geobarometers for terrestrial crust and mantle rocks. Divariant reactions useful as thermometers have proven to be relatively abundant, but barometers are scarce. Until recently, only one barometer for basic or ultrabasic compositions has been calibrated, making use of the  $Al_2O_3$  content of enstatite coexisting with pyrope-rich garnet.<sup>1</sup> This barometer is applicable only to high-pressure assemblages bearing garnet, which are rare on Earth and probably non-existent on other planetary bodies amenable to sampling.

A search for a new barometer applicable to basic and ultrabasic assemblages of lower pressure origin has led to preliminary experimental calibration of a barometer that can be applied to garnet-bearing rocks as well as the lower-pressure spinel- and plagioclase-bearing assemblages.<sup>2,3</sup> In this work, it was discovered that the concentration of Ca in forsterite coexisting with diopside and enstatite was pressure- as well as temperature-sensitive, and could be described by the equation:

$$P(kb) = (-2586 - Ca(ppmw) + 3.00T(^{\circ}K))/23.1$$

A suite of garnet lherzolite xenoliths from kimberlites of northern Lesotho, South Africa has been used to evaluate the accuracy of different formulations of thermometers and barometers.<sup>4</sup> This same suite of rocks was used to compare the olivine barometer to the enstatite barometer, using the diopside-enstatite miscibility gap<sup>5</sup> for temperature estimates. The olivine barometer met the petrologic constraints imposed by diamond, graphite and phlogopite stability, but the apparent fossil geotherm differed from that measured by enstatite-pyrope barometry in two respects: the slope of the low-temperature limb of the apparent geotherm ( $dT/dP$ ) is greater when measured by olivine barometry, and the scatter of P-T points at higher pressures is greater.

The application of any thermometer or barometer is subject to several potential problems. These include inaccurate calibration, incomplete calibration (i.e. effects of other solid solution components), and lack of equilibration in the rocks (e.g. different "locking" temperatures for different reactions during cooling of the rock, absence of certain critical phases). The enstatite-garnet barometer is not free of such problems, but evolving research by several authors is gradually reducing the errors. The olivine barometer is at the earliest stages of such an evolution. Nevertheless, an attempt is made herein to apply it to some terrestrial and lunar rock of relatively low pressure origin.

The terrestrial rocks are spinel lherzolite xenoliths from basalts of the southwest U.S. and of eastern China, and from the Moses Rock, Utah, kimberlite diatreme. All analyses, including for trace Ca in olivine, were

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obtained by electron microprobe. With care, Ca in olivine may be analyzed with precision of  $\pm 20$  ppmw ( $1\sigma$ ) on multiple grains<sup>2,3</sup>, corresponding to a pressure uncertainty from this source of about  $\pm 1$  kbar. We are grateful to R. L. Hervig for permission to use his high quality analyses for some of these rocks, from a manuscript in which he has calibrated an olivine-orthopyroxene Ca-Mg exchange barometer.

Application of thermobarometry to the terrestrial rocks quickly pinpointed a serious problem: six different thermometers yield temperature estimates on a single rock that span up to a  $450^\circ\text{C}$  range, with pressure estimates consequently ranging from 42.7 to -16.2 kbar! Two of these thermometers are based on the composition of diopside coexisting with enstatite,<sup>5</sup> with no corrections for solid solution effects. Because of the steepness of the diopside limb of the miscibility gap at relatively low temperatures, these thermometers are insensitive for the spinel lherzolites. They seem to be underestimating temperatures, commonly leading to negative pressure estimates.

Two other thermometers<sup>6,7</sup> are also based on diopside-enstatite equilibrium, but are expressed as exchange reactions and are corrected by theoretical and empirical factors for solid solution of other components, principally iron, in the pyroxenes. These yield higher temperatures, and higher pressures that are all above the  $\sim 10$  kbar value of the plagioclase lherzolite-to-spinel lherzolite transition. However, the pressure estimates tend to come out too high compared to the spinel lherzolite-to-garnet lherzolite transition, even when the major effects of Cr (ref. 8) are taken into account. A thermometer based on Fe-Mg exchange between olivine and spinel,<sup>9</sup> and one dependent upon Al in enstatite coexisting with spinel<sup>10</sup> also yield low temperature estimates.

The thermometer of Wells came closest to satisfying petrologic constraints imposed by plagioclase-spinel-garnet relationships. If the Wells temperatures are empirically lowered by  $84^\circ\text{C}$ , all pressure estimates fall below the garnet field while a few fall in the plagioclase field. If temperatures are lowered by  $44^\circ\text{C}$ , only one pressure estimate falls, within the garnet field and none within the plagioclase field. Thus Wells method is probably overestimating temperatures for spinel lherzolites by approximately  $44$ - $84^\circ\text{C}$ .

Two lunar rocks, dunite 72415<sup>11</sup> and troctolite 76535,<sup>11,12</sup> contain the appropriate mineral assemblage for pressure-temperature estimation, although the diopside in 76535 is found only in symplectites and may never have equilibrated with olivine or enstatite. Using Wells temperatures arbitrarily lowered by  $44$ - $84^\circ\text{C}$ , 72415 yields temperatures of  $948$ - $988^\circ\text{C}$  and pressures of  $6.4$ - $11.6$  kbar. For 76535, temperatures of  $865$ - $905^\circ\text{C}$  and pressures of  $28.4$ - $33.6$  kbar are calculated. In the case of 76535, these pressures correspond to a depth on the order of 600 km. This is clearly unreasonable, and supports the inference that the diopside is secondary<sup>11,12</sup> because the absence of diopside in the primary assemblage can allow Ca in olivine to drop below the calibration value, thus causing an overestimate of pressure.

The pressure estimate for 72415 corresponds to depths between about 130 and 230 km. This is in reasonable agreement with the estimate of 50-150 km excavation depth by Snee and Ahrens<sup>13</sup> based on shock features. Although the

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olivine barometer and appropriate thermometers need additional development, we are encouraged.

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